GEOLOGY AND LANDFORMS OF THE PERTH REGION

Department of Industry and Resources

BOB GOZZARD

Geological Survey of Western Australia

Eon	Era	System/Period		Lower boundary age (Ma)	Duration (Ma)	Rocks of Perth Region
Phanerozoic	Cenozoic	Quaternary		1.81		
		Neo-gene	Pliocene Miocene Oligocene	23.0		Superficial formations
		Paleo-gene	Eocene Paleocene	65.5	65.5	
	Mesozoic	Cretaceous		145.5	80.0	
		Jurassic		199.6	54.1	
		Triassic		251.0	51.4	
	Paleozoic	Permian		299.0	48.0	Rocks of the Perth Basin
		Carboniferous		359.2	60.2	
		Devonian		416.0	56.8	
		Silurian		443.7	27.7	
		Ordovician		488.3	44.6	
		Cambrian		542.0	53.7	
Proterozoic	Neoproterozoic			1000	458	Cardup Group
	Mesoproterozoic			1600	600	
	Paleoproterozoic			2500	900	
Archean				Lower limit is not defined		Rocks of the Yilgarn Craton

Generalized geological time scale (see also inside back cover for expanded Quaternary time scale)

GEOLOGY AND LANDFORMS OF THE PERTH REGION

by

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Cover: The Swan River snakes westward across the flat Swan Coastal Plain to enter the Indian Ocean at Fremantle (top of photo). Photograph courtesy of *The West Australian* newspaper

Frontispiece: Several shoreline platforms indicate former sea levels at Point Peron, Cape Peron

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Use the hammer and pick to dig deeper into a topic

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$4\,20\,^{000}$mE
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Mandurah
WESTERN
Dandalup
River
Mandurah
SOUTH
North
$64\,00\,^{000}$mN
116°
10 km
Peel Inlet
Murray River

INTRODUCTION

The local landscape has had a great influence on the development of the Perth Region

From the stability of the Darling Range to the dynamic coastal environments, the landscapes of the Perth Region have influenced the development of Perth. Many striking landforms and geological sections in the region provide insights to the geological history of the area, and the development of the landscape as we see it today:

- the landforms of the coastal areas record the fluctuating sea level, as a result of the glaciations of Pleistocene times;
- exposed riverbanks and subtle landforms of the Swan Valley reveal the history of past migrating river systems;
- sedimentary rocks of marine origin at the foot of the Darling Range are evidence for an ancient shoreline, when the ocean covered all of what is now the Swan Coastal Plain;
- and quarries on the Darling Plateau reveal the complex history of the ancient Yilgarn Craton, where belts of metamorphic rocks were intruded by large volumes of granite, and then eroded and deeply and intensely weathered over millions of years.

This booklet is a concise, informative, and simple guide aimed at providing a better understanding and appreciation of the geology of the Perth Region. It provides an insight into the range of natural features that characterize the Perth

Opposite page: Figure 1.
Location, access, and areas covered by this Guide

Localities visited in each chapter are shown as:

Region, explains the origin and evolution of various landscapes, and describes the underlying geology in relation to the landscape. It is aimed at those in secondary and tertiary education who require resource materials for teaching, and those with a basic understanding of geological principles, but it is also readily accessible to the layperson. If a geological term is not explained as part of the discussion, then it is written in bold and defined or described in more detail in the glossary.

For the purposes of this guide, the Perth Region includes most of the Perth metropolitan area between the Indian Ocean to the west and the Darling Range and Dandaragan Plateau to the east, and extends about 150 km from Moore River and Gingin Brook in the north to Mandurah in the south (Fig. 1).

It is not possible in a publication of this type to refer to all localities of interest within the Perth Region. Instead, only a select, but nonetheless representative, number of localities are discussed in detail. These localities, shown in Figure 1, are described following a route along the coast southwards returning north along the Darling Range.

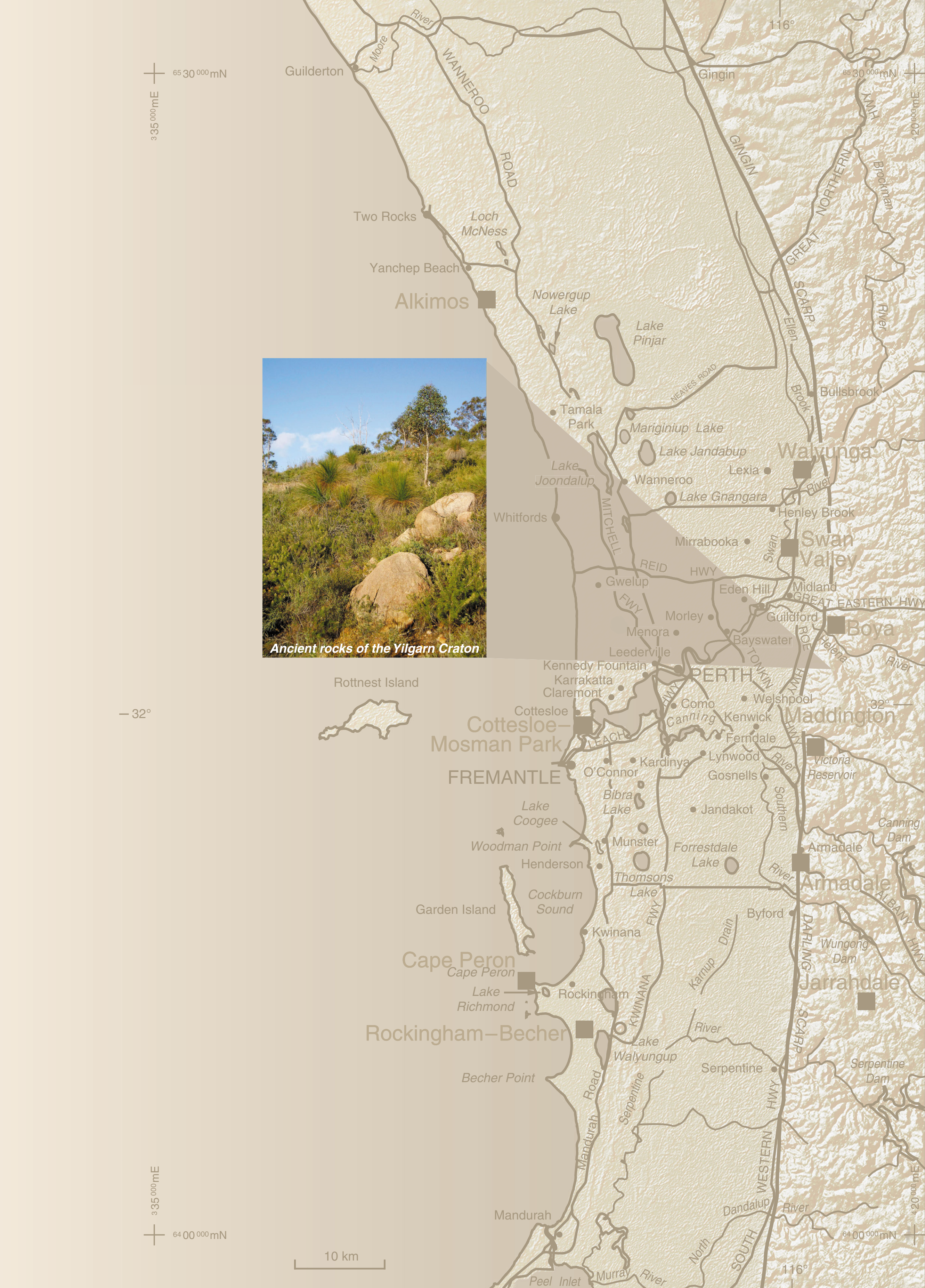
Source maps

Topographic maps and aerial photographs in Figures 9, 23, 32, 33, 37, 40, 43, 54, and 62 are reproduced by permission of Landgate (formerly Department of Land Information) Western Australia, Copyright Licence CL10/2003.

WARNING

Some of the sites mentioned in this guide have a significant danger from falling rocks, unstable edges, and dangerous overhangs, especially in coastal and disused quarry sections. Be aware of the state of the tides in coastal sections. Where appropriate, seek permission to enter sites on private land.


LIMESTONE RISK AREA
DANGER



Ancient rocks of the Yilgarn Craton

GEOLOGICAL SETTING

Ancient igneous and metamorphic rocks form the line of hills on the eastern horizon of Perth; younger, softer sediments make up the flat coastal plain. These two geological features define the character of the Perth Region

In geological terms, the Perth Region can be broadly divided into two features — the Darling Range, with its mix of ancient igneous and metamorphic rocks that form the line of hills to the east of Perth, and the coastal plain, with its thick succession of much younger and softer sedimentary rocks that form the flat plain to the west (see geology map, Figure 2). These features are the result of processes that have been operating over hundreds of millions of years. In fact, the geological history of the Darling Range can be traced back at least 2600 million years and possibly even further. The diagram on the inside front cover shows the ages of the rocks of the Perth Region in relation to a geological time scale.

An excursion to Cape Peron

The steep rise in topography from the eastern edge of the coastal plain up to the hills is called the Darling Scarp. This **scarp*** is the surface expression of the Darling Fault (Fig. 2), which is one of the major fractures in the Earth's crust — it extends for almost 1000 km, from east of Shark Bay, in the State's northwest, to Point D'Entrecasteaux on the south coast. Rapid erosion of the rocks along the scarp prior to the Cretaceous period has caused the scarp to retreat 1–3 km inland of the actual line of the fault.

The sedimentary rocks of the coastal plain lie in the Perth Basin (Fig. 2), which is part of a **rift valley** that developed between what is now Australia and a region that was to the north of India, when those continents were part of a supercontinent called **Gondwana** (Veevers et al., 1975). From time to time the sea flooded onto Gondwana, typically along narrow gulfs like the present-day Red Sea. These gulfs were destined to be the lines along which the supercontinent would fragment. The western and southern coastlines of Western Australia are the sites of such gulfs, and the Perth Basin is at the southern end of the gulf that extended south from the ancient **Tethys** Ocean.

The area east of the Darling Fault forms part of the Yilgarn Craton (Fig. 2) — a stable **craton** of Archean rocks that occupies much of the southern half of Western Australia. The oldest rocks in the Yilgarn Craton near Perth are metamorphic, and are found in a distinct belt along the Chittering Valley and near Toodyay (60 km northeast of Midland) and Canning Dam. Most of these rocks were originally muds and sands that were deposited in ancient seas between 3170 and 2830 million years ago (Wilde, 2001). Earth movements about 2800 million years ago altered these ancient sedimentary rocks into the metamorphic rocks we see today.

About 2600 million years ago large volumes of granitic **magma** were forced into the pre-existing metamorphic rocks before cooling and solidifying. **Monzogranite** is the most common rock type and is intimately mixed with the gneissic metamorphic rocks of the Chittering Valley.

After granite **magmatism** ended the Yilgarn Craton became stable. About 1400 million years ago a zone of deformation and mobilization developed on its western margin, and the Darling Fault was formed. Sedimentary rocks were deposited at the foot of the Darling Scarp that belong to the Cardup Group (Low, 1972; Playford et al., 1976) and consist of **conglomerate**, sandstone, siltstone, and shale. These sedimentary rocks are Proterozoic in age, possibly around 1400 million years old (Fitzsimons, 2003), and rest directly on the Archean **granites** of the Yilgarn Craton. They are unrelated to the sedimentary rocks in the Perth Basin.

Sediments from eroded continental rocks started to accumulate in the Perth Basin about 460 million years ago in the Ordovician period. This predominantly

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* Words written in bold type are defined in the glossary

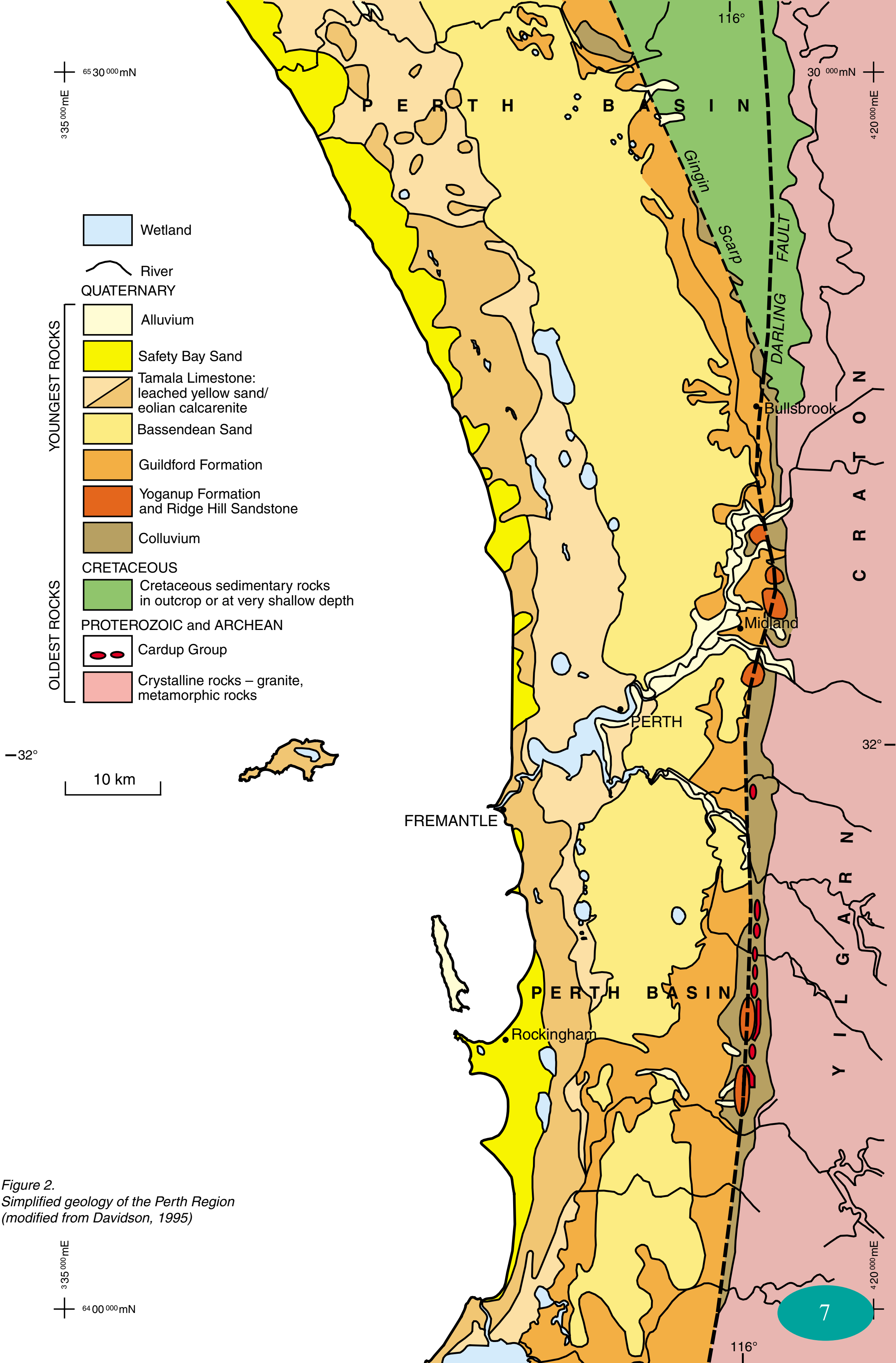


Figure 2.
Simplified geology of the Perth Region
(modified from Davidson, 1995)

fluvial sedimentation prevailed through to the Late Jurassic and earliest Cretaceous periods, some 140 million years ago. During these times major faulting took place in the basin along the zone of crustal weakness that had developed in this part of Gondwana.

During the Early Cretaceous period, **sea-floor spreading** was initiated west of the basin, and Gondwana began to break up as Greater India moved slowly away from Australia (Veevers and Cotterill, 1978). Initially, the whole of the Perth Basin was affected by uplift and erosion, but with the onset of sea-floor spreading much of the central and southern Perth Basin subsided, allowing the ocean to advance from the west. Large thicknesses of marine sediments were deposited as the sea over the Perth Basin grew wider and deeper.

Uplift and erosion occurred again throughout the basin in Late Cretaceous to Paleogene times. During the Paleogene there was initially some marine **carbonate** sedimentation followed by continental **clastic sedimentation**. The Paleogene was also a period when exposed rocks of the Darling and Dandaragan Plateaus were deeply and intensely weathered, resulting in a widespread cover of **lateritic materials**. Although more pronounced during the Paleogene, this **weathering** has continued until geologically recent times. These lateritic materials are iron rich and aluminium rich, and form strongly cemented, hard cappings to rocks on ridges (**duricrusts**), and discontinuous aprons of gravels up to 2 m thick on slopes flanking the ridges. The duricrusts and gravels overlie pale-coloured and mottled clays of intensely weathered granites, **dolerites**, and Cretaceous sedimentary rocks.

The youngest sedimentary rocks of the Perth Basin were deposited during Neogene and Quaternary times. They are **unconsolidated** or partly **lithified**, and formed during erosional and depositional events related to periods of higher and lower sea levels during Pleistocene and Holocene times (Quilty, 1977). These sedimentary rocks consist mainly of sands, limestones, silts, clays, and gravels of marine, estuarine, and **eolian** origin. Figure 3 comprises a series of geological sections to show the stratigraphic relationships of these younger formations. The diagram on the inside back cover is an expansion of the geological time scale covering the Quaternary period.

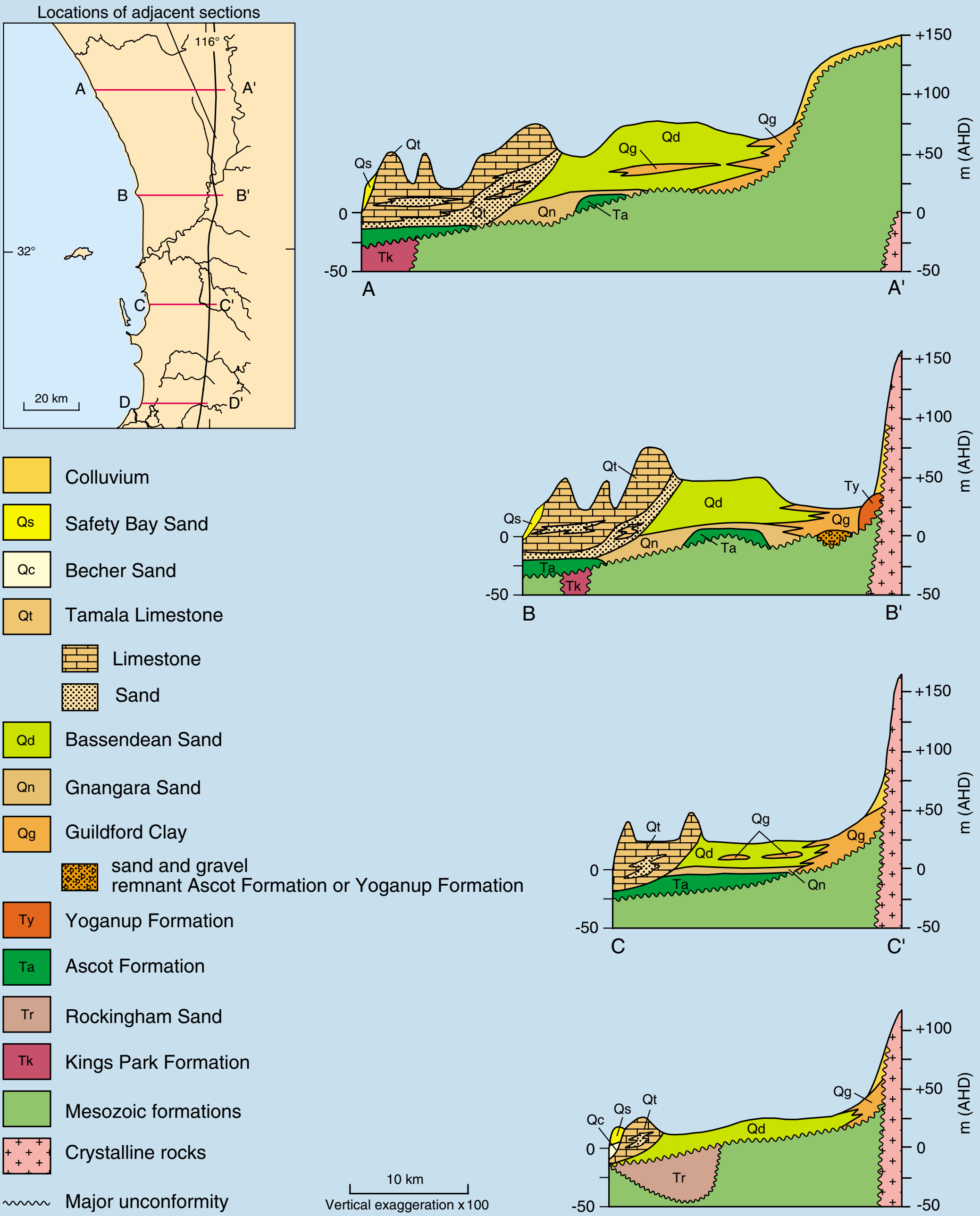
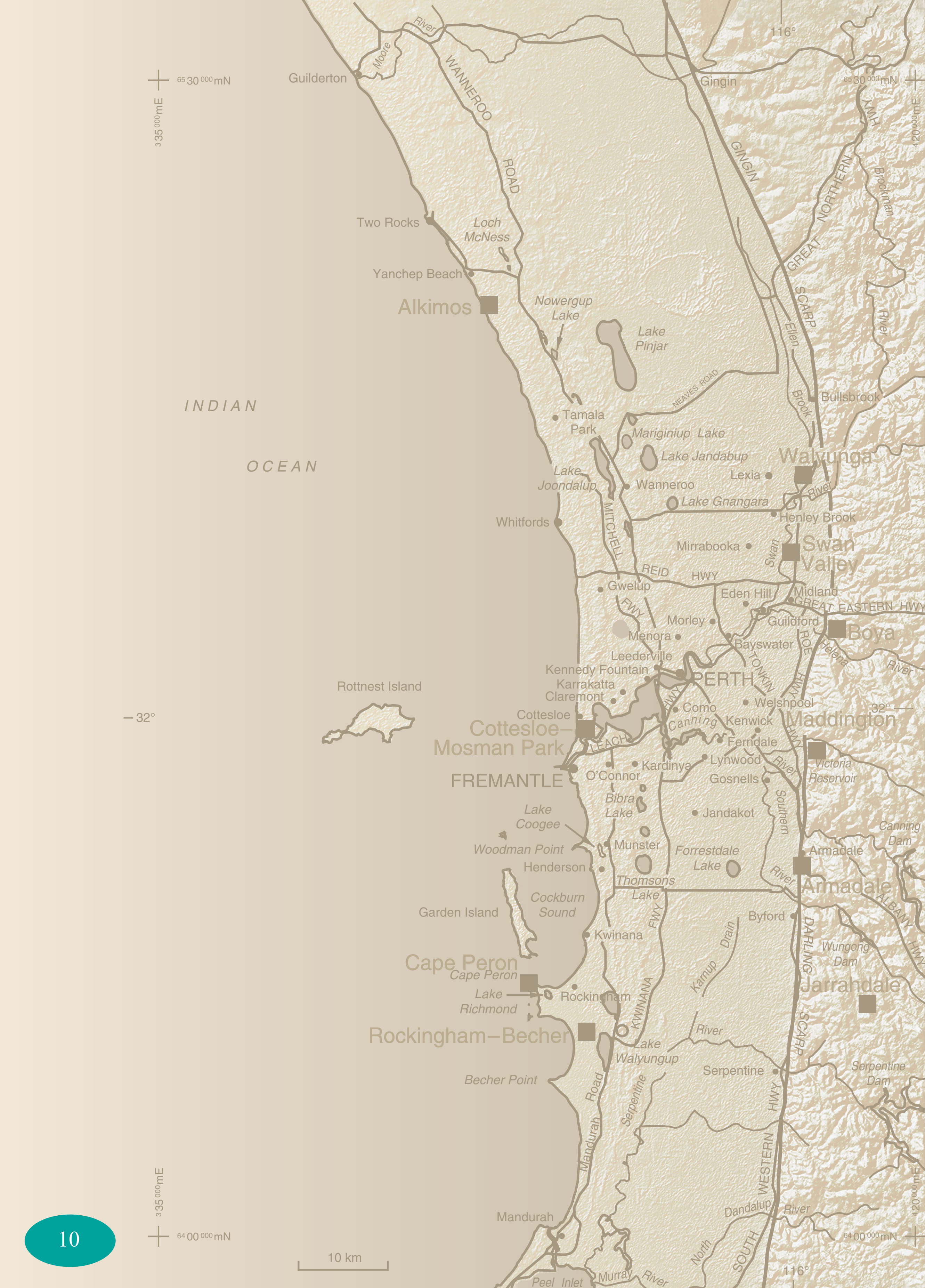


Figure 3.
Geological sections showing the stratigraphic relationships of the superficial formations (after Davidson, 1995)



Moore
River
Guilderton
WANNEROO
ROAD
Gingin
GINGIN
116°
65 30 000 mN
335 000 mE
420 000 mE
GREAT NORTHERN HWY
Brockman
Two Rocks
Loch McNess
Yanchep Beach
Alkimos
Nowergup Lake
Lake Pinjar
GREAT SCARP
Ellen
Brook
River
NEAVES ROAD
Bullsbrook
INDIAN
OCEAN
Tamala Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lake Joondalup
Lexia
Wanneroo
Lake Gnangara
River
Whitfords
MITCHELL
Henley Brook
Mirrabooka
Swan
Swan Valley
REID HWY
Gwelup
FWY
Eden Hill
Midland
GREAT EASTERN HWY
Morley
Guildford
Boya
Menora
Bayswater
ROE
Helena
River
Leederville
TONKIN
HWY
Kennedy Fountain
PERTH
Karrakatta
Claremont
Rottnest Island
32°
Cottesloe
Como
Welshpool
Canning
Kenwick
Maddington
Cottesloe–Mosman Park
LEACH
Ferndale
Lynwood
Victoria Reservoir
Kardinya
O'Connor
FREMANTLE
Gosnells
Bibra Lake
Jandakot
Southern
Lake Coogee
Canning Dam
Munster
Woodman Point
Forrestdale Lake
Armadale
Henderson
Thomsons Lake
Armadale
ALBANY
Cockburn Sound
Garden Island
Byford
DARLING
Kwinana
FWY
Drain
Wungong Dam
Cape Peron
Cape Peron
Karnup
Jarrandale
Lake Richmond
Rockingham
KWINANA
Rockingham–Becher
River
SCARP
Lake Walyungup
Serpentine
Becher Point
Road
Serpentine
Serpentine Dam
Mandurah
WESTERN
Mandurah
Dandalup
River
64 00 000 mN
10 km
North
SOUTH
Peel Inlet
Murray
River

LANDFORMS

Landforms of the region reflect its underlying geology — from the subdued hills of the eastern plateau to the flat coastal plain in the west

The Perth Region is characterized by a generally subdued topography, with the most obvious features being the coastal plain west of the Gingin and Darling Scarps, and the plateaus east of these scarps, which reflect the geology beneath. Figure 4 shows the gentle topography of the coastal plain as well as the steeper, dissected Darling Plateau area and the cliffs of the Darling Scarp.

This subdued landscape is the result of processes and events that have taken place over the last two to three million years. Fluctuating sea levels have changed the position of the coastline; sometimes the sea has lapped against the Darling Scarp, sometimes the land has extended out past Rottnest Island, and at other times the coast was in a similar position to the present-day coast.

Figure 5 shows the Perth Region divided into its two main physiographic provinces: the first encompassing the Darling Plateau and Darling Scarp to the east of the Darling Fault, and the second encompassing the Swan Coastal Plain and Dandaragan Plateau to the west of the fault (Pilgrim, 1979; Seddon, 1972).

Darling Plateau

Early explorers thought that the hills 30 km east of Perth formed a low mountain range, and hence on many maps of the Perth Region this feature is named the Darling Range. However, this line of hills is in fact an eroded **scarp** that forms the western edge of the extensive Darling Plateau, which has an average elevation of about 300 m AHD*.

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* All elevations quoted in this guide are relative to the Australian Height Datum (AHD), which is used as the zero height level for mapping purposes. It is the surface that passes through mean sea level at tide gauges across Australia

The Darling Plateau is not a smooth or flat surface as its name suggests — the action of streams and rivers has cut deeply into the surface, producing a landscape of hills and valleys. The bedrocks of the plateau are hidden beneath a mantle of **lateritic materials** and associated sands and gravels, which mask changes in the underlying geology. It is only where erosion has worn away these lateritic materials that the underlying ancient Archean rocks are exposed.

The lateritic materials are the weathering products of the **granite** and dolerite bedrocks of the plateau. Gravels and gravelly sands flank the lateritic ridges, and these grade downslope into the **alluvial** sands and silts of the valley streams and swamps.

The eastern part of the Darling Plateau is characterized by flat-topped hills bound by small erosional scarps called breakaways. These hills lack the protecting mantle of cemented lateritic gravels typical of the ridges and hills to the west (Mulcahy, 1968). In the eastern part of the Perth Region and beyond, prominent hills, sometimes called **monadnocks** (Jutson, 1950), protrude above the general level of the Darling Plateau and probably represent part of the land surface before it was lateritized. They include Mount Dale (20 km east-northeast of Canning Dam) and Mount Solus (15 km southeast of Serpentine Dam), and the hills that divide the Canning and Serpentine drainage systems between Mount Cooke (24 km east of Serpentine Dam) and Eagle Hill (18 km southeast of Canning Dam).

The valleys of the Darling Plateau show a distinct trend from west to east. They can be divided along their river courses into three valley forms based on the nature of their slopes, floors, and the erosional modifications to the weathered material (Churchward and McArthur, 1978). In classic physiographic terminology, the valleys exhibit youthful features near the Darling Scarp to mature features near the eastern hills — valleys to the west have steep rocky slopes and narrow, flat valley floors; valleys in the central areas have high relief (200 m), 30° slopes in weathered rock and lateritic material, and well-defined valley floors with well-developed river terraces; and to the east the valleys have 90–120-m relief, with smooth rounded slopes (<15°) mantled by lateritic material and country rock, and well-developed, wide river terraces in broad valley floors.

The Darling Scarp (Fig. 4) forms the western edge of the Darling Plateau, and is most prominent south of Bullsbrook, where there is an abrupt 430-m rise from the coastal plain to the edge of the Darling Plateau over a horizontal distance of only 1 to 2 km. In this area, major valleys such as those of the Swan, Helena, Canning, and Serpentine rivers dissect the scarp.

Opposite page: Figure 4.
*The contrast between the subdued topography of the Swan Coastal Plain (green), and the dissected Dandaragan Plateau and Darling Plateau (orange-brown) is strikingly displayed in this image processed from **SRTM** data. Erosion has caused the Darling Scarp to retreat eastwards from the Darling Fault (see also Geological Setting chapter)*


DANDARAGAN
PLATEAU
GINGIN SCARP
Yanchep Beach
Bullsbrook
PERTH
FREMANTLE
Rockingham
SWAN COSTAL PLAIN
DARLING SCARP
DARLING PLATEAU

North of Bullsbrook the Darling Scarp is only 90 m high at most and is only evident as a series of broken **spurs** and numerous deeply dissected, flat-topped hills (Miles, 1938).

Dandaragan Plateau

The Dandaragan Plateau lies north of Bullsbrook and forms a wedge-shaped area between the Darling Scarp to the east and Gingin Scarp to the west (Fig. 4). It has an elevation of about 200 m and consists of Cretaceous sedimentary rocks covered by sand and lateritic material. In contrast to the Darling Plateau, there are few rivers and streams on the Dandaragan Plateau, and therefore erosion has been minimal since the lateritic material was formed.

Swan Coastal Plain

The Swan Coastal Plain (Saint-Smith, 1912) extends west from the Darling and Gingin Scarps to the Indian Ocean. It includes several geomorphological units (McArthur and Bettenay, 1960), which are distributed roughly parallel to the present-day coastline (Fig. 5). The sediments of these units were mainly deposited by rivers (alluvial) in the east and wind (**eolian**) in the west.

Ridge Hill Shelf

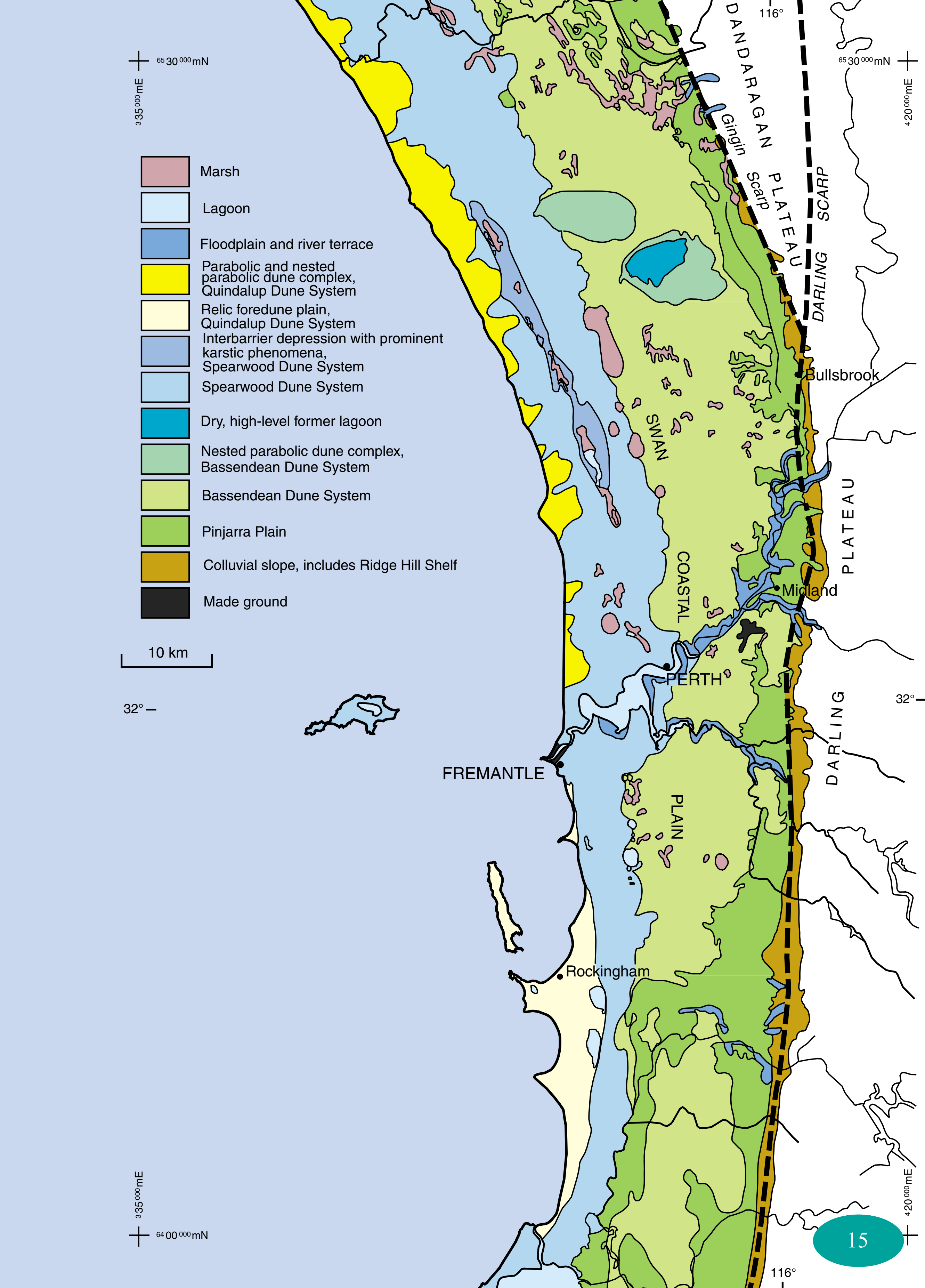
The most easterly feature of the coastal plain is the Ridge Hill Shelf. This is a remnant of a former, more-continuous unit that existed in a narrow zone 1.5 to 3 km wide along the Darling Scarp, and now forms part of the foothills (**piedmont zone**) of the scarp. It consists of the remnants of two former shoreline deposits — the Ridge Hill Sandstone and the Yoganup Formation. The younger Yoganup Formation lies to the west of the Ridge Hill Sandstone and at a lower elevation. Both of these shoreline deposits are highly weathered.

A series of **colluvial** slopes are also part of the Darling Scarp piedmont zone. These slopes are made up of **alluvial fans** deposited by streams at the bottom of the scarp and colluvial fans deposited by downslope transport of material on the face of the scarp.

Pinjarra Plain

The Pinjarra Plain is an alluvial tract of **unconsolidated** clays and loams, with minor amounts of limestone, extending west from the Ridge Hill Shelf for 1.5 to 5 km. It consists of alluvial fans near the scarp and floodplains along the rivers. The two broadest areas of the Pinjarra Plain in the Perth Region are the Swan Valley and Serpentine River flats. The elevation of the plain increases northward, from 7 m east of Perth to 75 m at Bullsbrook. The alluvial fans are higher along

Opposite page: Figure 5.
Generalized geomorphology of the Perth Region (modified from Davidson, 1995)


Marsh
Lagoon
Floodplain and river terrace
Parabolic and nested parabolic dune complex, Quindalup Dune System
Relic foredune plain, Quindalup Dune System
Interbarrier depression with prominent karstic phenomena, Spearwood Dune System
Spearwood Dune System
Dry, high-level former lagoon
Nested parabolic dune complex, Bassendean Dune System
Bassendean Dune System
Pinjarra Plain
Colluvial slope, includes Ridge Hill Shelf
Made ground
10 km
6530 000mN
335 000mE
420 000mE
6400 000mN
116°
32°
DANDARAGAN PLATEAU
Gingin Scarp
DARLING SCARP
DARLING PLATEAU
SWAN COASTAL PLAIN
Bullsbrook
Midland
PERTH
FREMANTLE
Rockingham

the courses of the larger streams that emerge from the Darling Plateau, but farther west they merge imperceptibly with floodplain and estuarine sedimentary rocks.

Bassendean Dune System

The Bassendean Dune System is a series of shoreline deposits and coastal dunes in a 15 km-wide zone between the Spearwood Dune System and the Pinjarra Plain. It developed during several dune-building events that took place over a period of about 100 000 years in an interglacial period that began about 240 000 years ago. The dunes developed on a broad ridge of older, dominantly marine and lacustrine deposits that were eroded and reworked, so that the dune system is superimposed on several planed surfaces. The dunes consist of low hills of quartz sand with sandy swamps in depressions (**swales**) between the dunes. About 10 km west of Bullsbrook the dunes have an elevation of up to 100 m.

Spearwood Dune System

The Spearwood Dune System forms a belt 3 to 15 km wide, west of the Bassendean Dune System. The dunes are large-scale, convex, asymmetric, topographically irregular ridges that reach heights of 95 m in places. The Spearwood dunes are younger than the Bassendean dunes, but are still late Quaternary (Pleistocene) in age. The shape of the dunes suggests that they were formed as large-scale, bare, dune sheets that advanced over the land surface.

There are three lines of dunes separated by discontinuous, partially infilled, linear depressions that are thought to be former shorelines, where lagoons were cut off by developing **foredunes** from a **prograding shoreline**. The three lines of dunes decrease in age towards the west.

The Spearwood dunes comprise the eolian parts of the Tamala Limestone — medium- to coarse-grained **calcarenite**, composed largely of broken fossil shell fragments and various amounts of quartz sand. Large-scale **cross-bedding** is common, as are fossil soil horizons (**paleosols**) and calcified fossil root structures (**rhizoliths**). Leached yellow quartz sand is closely associated with the calcarenite, and represents the decalcified remnants of the calcarenite dunes. Some patches of calcareous sand remain, especially close to calcarenite outcrops.

In the Cottesloe – Mosman Park area, the calcarenite is interbedded with a number of thin, lenticular limestones of marine origin.

North of Wanneroo, caves, **sinkholes**, gorges, and **dolines** have developed in the calcarenite in the linear depression that separates the east and central lines of dunes. These solution cavities are particularly common east of Yanchep, but large cavities are also developed at the water table beneath most of the coastal strip of the Spearwood dunes.

In caves of the Yanchep National Park, dissolved calcium carbonate has been redeposited as impressive cave deposits that vary in form, from small twig-like formations (helictites) to **stalactites**, **stalagmites**, and large **flow stones**.

Quindalup Dune System

The Quindalup Dune System is the most westerly dune system of the Swan Coastal Plain. It consists of unconsolidated calcareous sands, and forms the more obvious landforms along the coast — **parabolic dunes** and relict **cuspate beach-ridge plains**. The dunes are Holocene in age (McArthur and Bettenay, 1960), and some are still forming along the coastline today. U-shaped, large-scale parabolic dunes dominate the coast north of the Swan River, and in places some dunes extend over 10 km inland. The western margin of the dunes is truncated along the coast and forms a steep cliff, at the base of which is a narrow sandy beach.

The relict cuspate beach-ridge plains dominate the coast south of the Swan River. At Woodman Point and between Kwinana and Mandurah, these plains extend inland beyond the general trend of the coast. Less obvious examples are to be seen north of the river at Whitfords, Burns Beach, Quinns Rock, and Two Rocks. In most cases these plains are asymmetric in shape, and abandoned shoreline positions are marked by relict **beach ridges**. The southern flanks of the plains terminate in dune cliffs, whereas the northern flanks comprise a series of low ridges parallel to the shore. In most cases, growth of the plains now appears to have ceased and erosion is active on the southern flanks.

The rivers that cross the coastal plain cut across all three of these mainly northerly trending dune systems. In their lower reaches, the courses of the Swan and Canning Rivers appear to have been controlled to some extent by the dune topography. Bull Creek, Melville Water, and Freshwater Bay all occupy northerly trending interdunal depressions. Farther south, the Serpentine River flows west towards the coast before swinging south, parallel to the coast, along the boundary of the Spearwood and Bassendean Dune Systems, before flowing into the Peel Inlet.

Flanking the rivers are clay-rich floodplains and river terraces of recent origin. The Swan Valley in particular exhibits a number of broad river terraces at several levels above the present river level.

Coastal landforms

Marine deposits of Pleistocene age are fairly widespread along the west coast of Western Australia. In the Perth region limestones of this age form discontinuous pockets and lenses of shelly calcarenites, interbedded with eolian calcarenites of the Spearwood Dune System. Together these shallow-marine and beach deposits

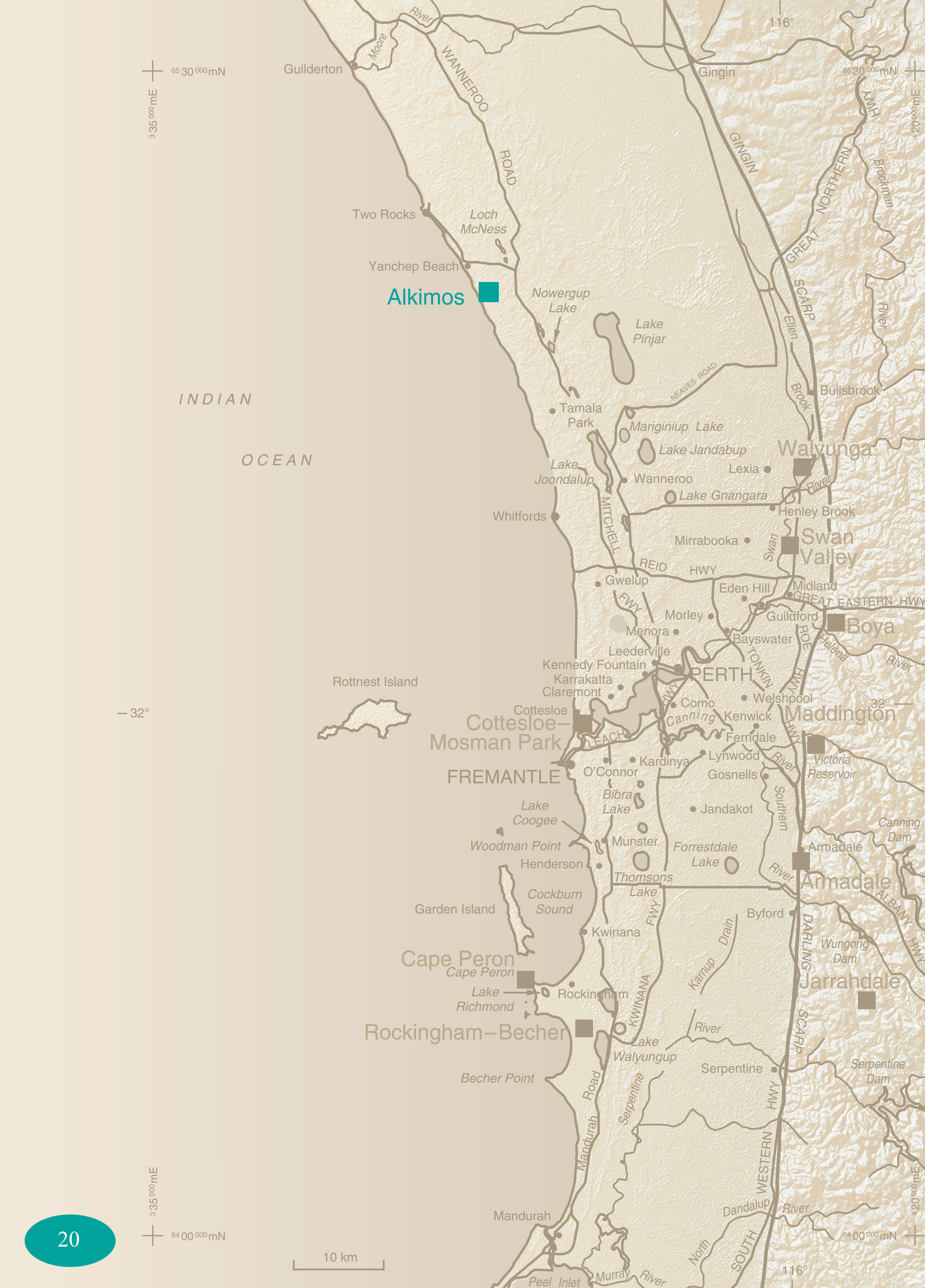
are known as the Tamala Limestone (Playford et al., 1976), and they form a series of cemented coastal sand dunes. The offshore reefs and islands in the region represent drowned lines of these sand dunes that were deposited during periods of lower sea level. At least three chains of offshore reefs and islands can be distinguished south of Fremantle: the inner one includes the limestone outcrop at Woodman Point and a number of shoals and reefs north and south of Woodman Point, including Fish Rocks; the middle chain includes Rottnest Island, Carnac Island, Garden Island, Cape Peron, Bird Island, Seal Island, Penguin Island, and the Murray Reefs (see photograph below); and the outer chain includes the Five-Fathom Bank and terminates at Rottnest Island.

Outcrops of marine units within the Tamala Limestone can be seen along the river and ocean shorelines around the Cottesloe – Mosman Park area, at Beenyup cutting immediately south of the Ocean Reef boat harbour, in the cliffs below the Marmion Angling and Aquatic Club in Marmion, and in the quarries on Tims Thicket Road at Dawesville, 16 km southwest of Mandurah.

A number of interesting features are developed within exposures of Tamala Limestone across the Perth Region. These include paleosols, rhizoliths, calcreted surfaces (**beach rock**), **karstic** features (e.g. sinkholes, caves), **raised beaches**, and elevated shoreline platforms.

South of the Perth Region, between Mandurah and Bunbury, fossiliferous marine and estuarine limestones within the Tamala Limestone formation form the Yoongarillup Plain — a strip of low, undulating ground between the Spearwood and Quindalup Dune Systems (Semeniuk, 1990).


Part of the middle chain of offshore reefs and islands



Alkimos
INDIAN
OCEAN
Guilderton
Moore
River
WANNEROO
ROAD
Gingin
GINGIN
116°
65 30 000 mN
3 35 000 mE
4 20 000 mE
BRAND HWY
GREAT NORTHERN
Brockman
River
Two Rocks
Loch
McNess
Yanchep Beach
Nowergup
Lake
Lake
Pinjar
SCARP
Ellen
Brook
NEAVES ROAD
Bullsbrook
Tamala
Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lexia
Lake
Joondalup
Wanneroo
River
Lake Gnangara
Henley Brook
Whitfords
MITCHELL
Mirrabooka
Swan
Swan
Valley
REID
HWY
Gwelup
FWY
Eden Hill
Midland
GREAT EASTERN HWY
Morley
Guildford
Boya
Menora
Bayswater
ROE
Helena
River
Leederville
TONKIN
Kennedy Fountain
Karrakatta
Claremont
PERTH
HWY
Rottnest Island
Welshpool
32°
Cottesloe
Como
Canning
Kenwick
Maddington
Cottesloe–
Mosman Park
LEACH
Ferndale
Lynwood
Kardinya
River
Victoria
Reservoir
FREMANTLE
O'Connor
Gosnells
Bibra
Lake
Southern
Lake
Coogee
Jandakot
Canning
Dam
Woodman Point
Munster
Forrestdale
Lake
Armadale
Henderson
River
Thomsons
Lake
Armadale
Cockburn
Sound
ALBANY
Garden Island
FWY
Byford
DARLING
HWY
Kwinana
Drain
Wungong
Dam
Cape Peron
Cape Peron
Karnup
Jarrahdale
Lake
Richmond
Rockingham
KWINANA
Rockingham–Becher
River
Lake
Walyungup
SCARP
Serpentine
Serpentine
Dam
Becher Point
Road
Serpentine
HWY
Mandurah
WESTERN
Dandalup
River
Mandurah
64 00 000 mN
10 km
North
SOUTH
Peel Inlet
Murray
River

ALKIMOS

Large parabolic dunes are common along the coast — and some are still forming today

Figure 6. Location of the Alkimos dune complex

Some of the most obvious landforms along the coast of the Perth Region are the large, **transgressive**, **parabolic dunes** (Bird, 1984) of the Quindalup Dune System, the most westerly dune system along the coast. These coastal landforms include various types of beaches and dune complexes, some of which are forming today. They are the geomorphological expression of the Holocene geological formation called the Safety Bay Sand (Passmore, 1970; Playford and Low, 1972), and are composed of **unconsolidated** to weakly consolidated calcareous sand. They almost completely blanket the seaward margin of the westernmost ridge of the Spearwood Dune System.

In some places, for example at Mullaloo, the dunes of the Quindalup Dune System extend more than 10 km inland. The western margin of the dunes is truncated along the coast to form a steep cliff fronted by a narrow sandy beach. The majority of the dunes are stabilized by vegetation, although plant density is low on the dune crest because of the high rate of **leaching**, the low water table, and greater wind exposure. Destruction or removal of the vegetation on the crests or former downwind faces of the dunes may cause destabilization, resulting in **blowouts** and reactivation of the dunes.

There appears to be a relationship between the inland extent of the dune complexes and the size of the adjacent beach (Semeniuk et al., 1989). Where limestone cliffs form the coast, beaches are confined to small sandy coves between limestone headlands. Behind these beaches, small dune complexes of the Quindalup Dune System are perched on the Spearwood Dune System. In contrast, where the dune complexes of the Quindalup Dune System extend farther inland, the beaches are larger.

About 8 km south of Yanchep, at Alkimos (Fig. 6), there is an exceptional example of the development of a parabolic dune complex of the Quindalup Dune System. This complex is probably the best example in the Perth Region that has not been encroached on by urbanization and is still accessible for scientific study. Similar but smaller scale dune complexes can be seen elsewhere along the coast of the Perth Region, especially north of the Swan River around Two Rocks and Yanchep, at Burns Beach, and further south at Trigg Bushland Reserve.

The parabolic dunes at Alkimos are scrub-covered, semi-discrete, high, U-shaped sand ridges, with steep slopes on the advancing faces. The dunes were initiated as blowouts, and would have advanced downwind away from the initial source of erosion, with the axes of the dunes parallel to the direction of the main sand-moving winds (southwesterlies). Figure 7 shows the most common coastal-dune landforms of the Perth Region.

The dunes have been deposited in a number of cycles, with periods of dune formation separated by periods of stability. Four phases of dune activity have been identified, and younger dunes are superimposed on the older (McArthur and Bartle, 1980). The older dunes typically extend farther inland. These four phases

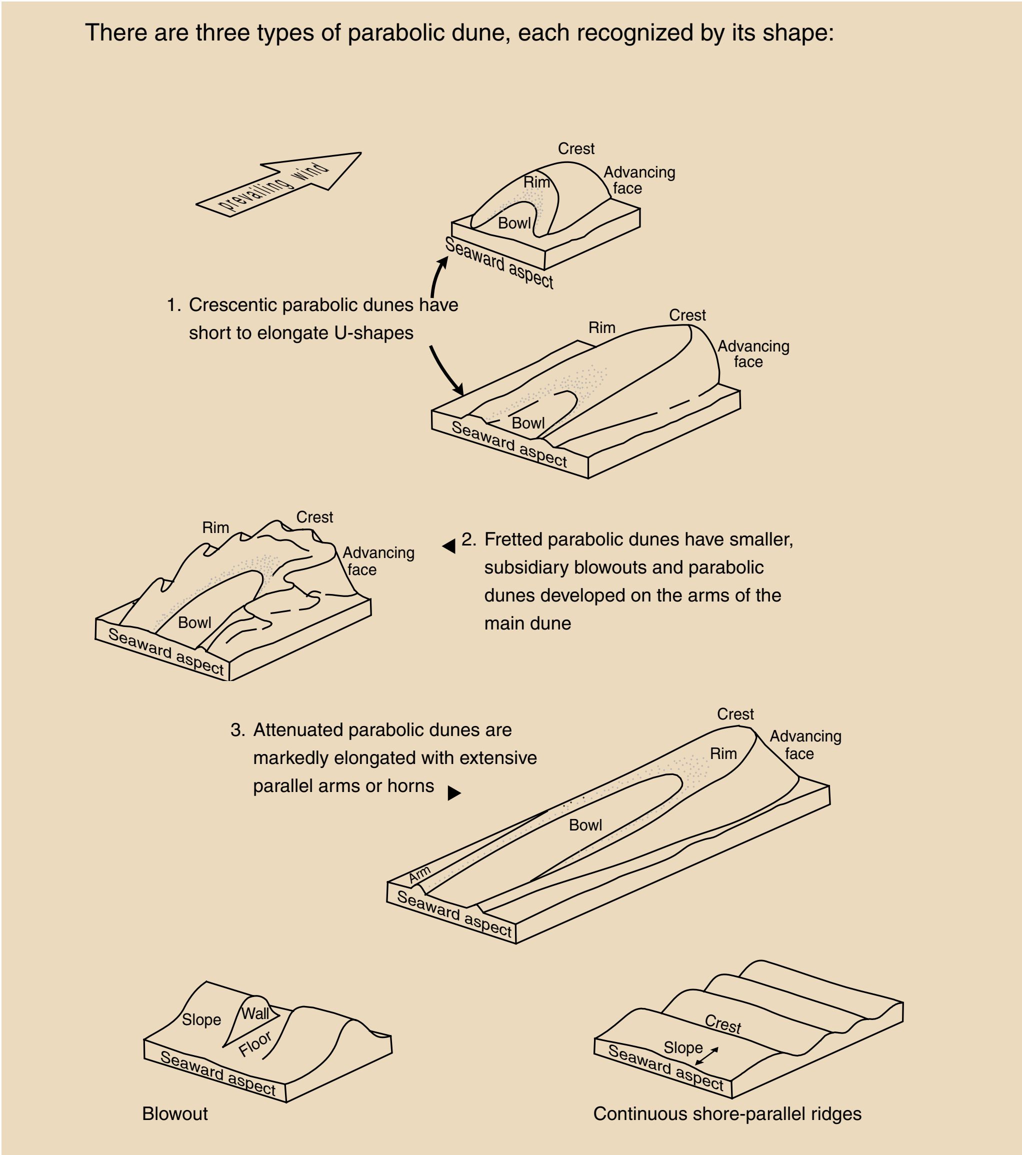


Figure 7.
The most common coastal-dune landforms of the Perth Region (adapted from Semeniuk et al., 1989)

are defined on the basis of the shape, stability, vegetation cover, and soil-profile development of the dunes (Fig. 8).

The oldest phase (Q1) forms a series of dunes of low relief with symmetrical cross sections and an overall low profile. Slopes on the arms and crest tend to be about 10–15°. Below the soil (**pedological horizon**), which tends to be rich in organic matter, there is a tendency for the sand to become partially consolidated and cemented. In places, erosion of the dune has exposed the cemented core.

The second phase (Q2) is the most extensive and extends up to 4 km inland as large-scale, crescentic and attenuated parabolic dunes that show some tendency to fretting on the advancing crest and arms. The dunes of this phase have steep slopes and an overall higher relief than dunes of the Q1 phase. Below the organic-rich soil profile the dune cores are cemented. As with the Q1 phase, erosion of the dune has exposed the cemented core in places.

In general, the third phase (Q3) is not as extensive as the older two phases. It is easily recognizable and can be clearly differentiated from the older two phases by virtue of its steep slopes, smooth profile, and greater relief. The development of pedological horizons is not as marked as in the older two phases, and cementation of the underlying sand is minimal to non-existent.

The youngest phase (Q4) is the least extensive of the four phases and is confined to the seaward margin of the dune complex. The dunes of this phase tend to be small crescentic dunes with steep outer faces and more-gentle inner slopes. Being the youngest phase, the dunes have a fresh morphology, and deep bowls and other depressions are contained by the arms of the parabolic dunes. In a few places, conical-hill residual dunes can be seen within the migrating parabolic dunes.

The relative ages of the four phases of the Quindalup Dune System are clear, and all four phases are Holocene in age (Passmore, 1970), but little work has been done to determine their absolute age. The oldest phase (Q1) is probably of the order of 6500 years old, and may be related to the 2.5-m fall in sea level that occurred at that time (Searle and Woods, 1986). The youngest phase (Q4) is probably only a few hundred years old.

In contrast to the dunes forming along the coastline of the Perth Region today, the Alkimos and similar dune complexes extend much farther inland. At Alkimos this distance is about 4 km but, as mentioned above, some of the Holocene dunes extend as much as 10 km inland. This suggests that the local climate during the formation of these dune complexes was more arid than at present and that the prevailing (southwesterly) winds were stronger. This concurs with Backhouse (1993), who found that a period of aridity commenced in the Holocene about 6000 to 5000 years ago.

Getting there

The Alkimos dune complex lies on private land between the coast and Wanneroo Road. Although many four-wheel drive tracks criss-cross the area, permission to enter the private property should be obtained from the landowners.

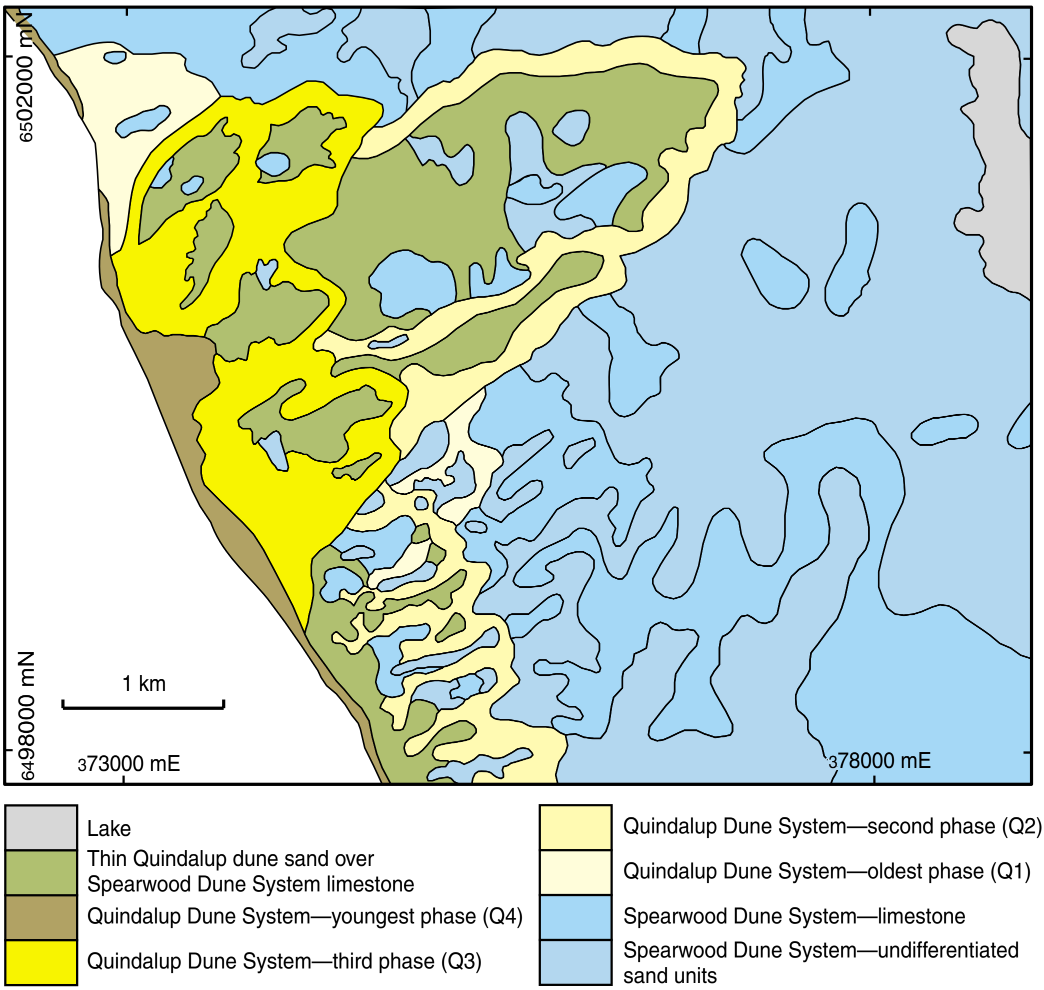
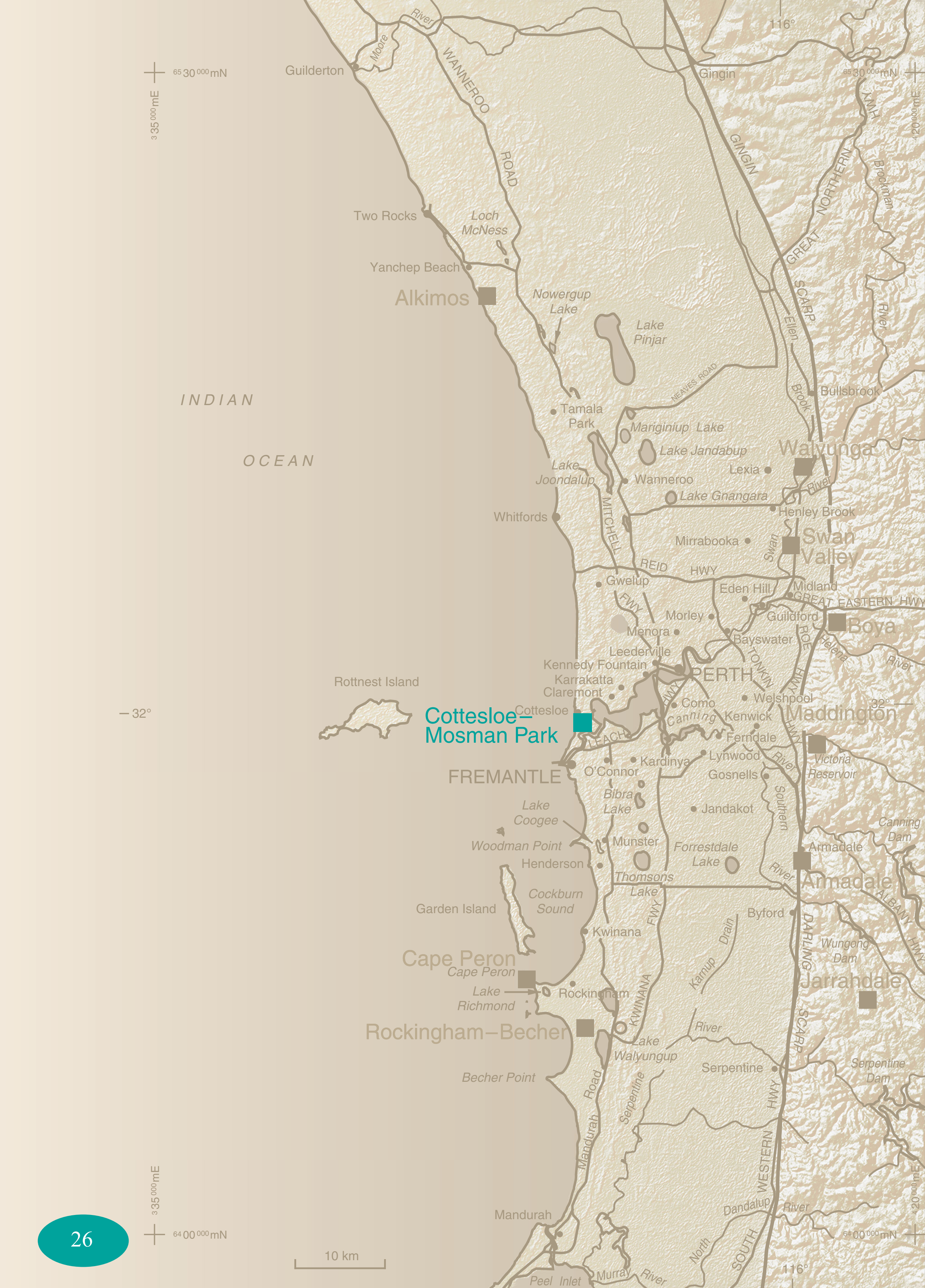


Figure 8.
Geomorphological sketch map of the Alkimos dune complex. Location of diagram shown on Figure 6


INDIAN
OCEAN
Guilderton
Moore
River
WANNEROO
ROAD
Gingin
GINGIN
116°
65 30 000 mN
3 35 000 mE
4 20 000 mE
Two Rocks
Loch McNess
Yanchep Beach
Alkimos
Nowergup Lake
Lake Pinjar
NEAVES ROAD
GREAT
NORTHERN
HWY
SCARP
Brockman
River
Ellen
Brook
Bullsbrook
Tamala Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lake Joondalup
Wanneroo
Lexia
Lake Gnangara
Henley Brook
Whitfords
MITCHELL
Mirrabooka
Swan Valley
Swan
REID
HWY
Gwelup
FWY
Eden Hill
Midland
GREAT EASTERN HWY
Morley
Guildford
Boya
Menora
Bayswater
ROE
Helena
River
Leederville
TONKIN
Kennedy Fountain
PERTH
Karrakatta
Claremont
HWY
Rottnest Island
32°
Cottesloe
Cottesloe–Mosman Park
Como
Welshpool
Canning
Kenwick
Maddington
LEACH
Ferndale
FREMANTLE
Kardinya
Lynwood
O'Connor
Gosnells
Victoria Reservoir
Bibra Lake
Jandakot
Southern
Lake Coogee
Canning Dam
Woodman Point
Munster
Forrestdale Lake
Armadale
Henderson
Thomsons Lake
Cockburn Sound
Garden Island
FWY
Byford
ALBANY
DARLING
Kwinana
Drain
Wungong Dam
Cape Peron
Cape Peron
Karnup
Jarrahdale
Lake Richmond
Rockingham
KWINANA
Rockingham–Becher
River
Lake Walyungup
Becher Point
Serpentine
Serpentine Dam
Road
Mandurah
WESTERN
Dandalup
Mandurah
64 00 000 mN
10 km
North
SOUTH
Peel Inlet
Murray
River

COTTESLOE – MOSMAN PARK

This is an ideal place to see eolian and marine units of the Tamala Limestone outcropping around the river and ocean shorelines

Figure 9. Location of Pleistocene marine units in the Cottesloe – Mosman Park area

The Cottesloe – Mosman Park area is an ideal place to observe the results of sea-level changes during the Middle to Late Pleistocene (750 000 to 10 000 years ago), in a time when the Earth experienced dramatic climate changes and underwent its last period of glaciation. Evidence of fluctuating sea levels is recorded by the **eolian calcarenites** of the Tamala Limestone and interfingering shallow-marine units. Marine deposits of Pleistocene age are fairly widespread along the coast of Western Australia between the North West Cape in the north and Augusta in the south, and many of these deposits have been used to determine the sea-level history of the west coast during this period (Veeh, 1976; Price et al., 2001).

The Tamala Limestone (Playford et al., 1976) mainly consists of medium- to coarse-grained calcarenite, which is composed of broken **mollusc** and **foraminifera** shell debris and variable amounts of quartz sand. There is marked variation in the rock types within the unit, and fossil soils (**paleosols**) and calcified root structures (**rhizoliths**) are common. The eolian origin of parts of the formation is shown by large-scale **cross-bedding.** The marine members within the Tamala Limestone form discontinuous pockets and lenses of shelly calcarenites, and are readily distinguishable from both the eolian calcarenites and from each other on the basis of the fossils they contain, the degree of preservation of the fossils, and the type and degree of modification that they have undergone since their deposition (Kendrick et al., 1991).

In the Cottesloe – Mosman Park area there are a number of marine units within the Tamala Limestone that outcrop around the river and ocean shorelines (Fig. 9). Somerville (1920) was the first to describe the shelly marine units of the Cottesloe – Mosman Park area, and considered them as evidence for uplift of the lower portion of the Swan River area. Since then, numerous studies have been undertaken to determine the absolute ages of the units so that the marine units can be placed within a regional time (**chronostratigraphic**) framework for western and southern Australia (Fairbridge, 1953, 1954; Hewgill et al., 1983; Kendrick, 1960; Kendrick et al., 1991; Murray-Wallace and Kimber, 1989; Murray-Wallace et al., 1988).

Peppermint Grove

The foreshore of the Swan River at Peppermint Grove (Fig. 9) is an excellent location to observe the relationship between eolian calcarenites and shelly marine units of the Tamala Limestone. The marine units here constitute the **type section** of the Peppermint Grove Member (Fairbridge, 1954), and they can be seen to interfinger with the eolian parts of the Tamala Limestone.

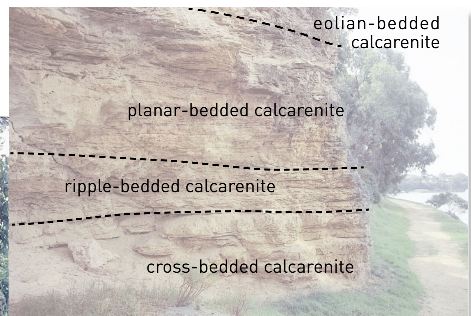
The northern end of the outcrop, about 80 m north-northeast of the Scotch College boatshed, is a section that records the continuing retreat of the sea (**regression**), from a shallow-marine environment to a beach environment

(Fig. 10). The base of the section comprises a 1.4 m-thick, medium-scale cross-bedded calcarenite unit, indicative of offshore deposition in shallow water. In this environment, water currents cause ripples in the sediment to migrate, and as the lee sides avalanche, dipping foreset laminae are produced. The orientation of the cross-beds therefore indicates the direction of the currents. The cross-bedded calcarenite is overlain by a 0.9 m-thick, ripple-bedded calcarenite unit. Ripple beds form as a result of the oscillating motion of waves, and therefore indicate deposition in a near-shore surf zone. The ripple-bedded unit is overlain by a 1.6 m-thick, planar-bedded calcarenite, which indicates high-energy movement of sediment in a foreshore beach environment.

After further regression, this location became relatively high compared to the retreating shoreline, and the top of the planar-bedded unit became an erosional surface on which **calcrete** developed during a phase of **subaerial** soil formation and weathering. Above this calcrete paleosol is a variably thick (up to 0.6 m), slightly shelly calcarenite that is up to 7.3 m above the present sea level. This indicates that there was a later episode of marine deposition, during which the sea level was about 7.5 m higher than it is today (Playford et al., 1976).

A thick (2.5 m) sequence of large-scale cross-bedded calcarenite overlies the complete marine sequence. These large-scale cross-beds represent the

Figure 10.
Shallow-water cross-bedded and ripple-bedded marine calcarenite grading up into planar-bedded beach calcarenite at Peppermint Grove (MGA 384020E 6459370N)



avalanching lee sides of migrating dunes through the action of wind, and indicate that a major dune-building episode followed the period of marine and shoreline deposition.

In the central part of the section, about 55 m north-northeast of the boatshed, near the prominent cave, there is a sequence similar to that farther north. However, in this location a thick development of **brecciated** calcrete drapes the underlying calcrete and marine units (Fig. 11). This brecciated calcrete is probably cemented beach material (**beach rock**) that later formed a low fossil cliff. An unusual feature at this locality is the eye-catching brown and black limestone pebbles within the brecciated calcrete (Fig. 12). These pebbles appear to be restricted to a single vertical zone and may represent the remains of a **neptunian dyke**, which filled a former undersea fissure or hollow.

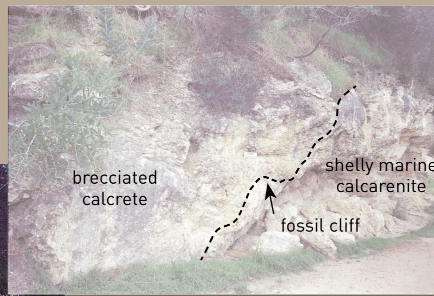
At the southern end of the section, about 40 m north-northeast of the boatshed (Fig. 13), a 1.7 m-thick unit of abundantly shelly calcarenite abuts and overlies the brecciated calcrete. This unit thins to the south and is overlain by a 0.8 m-thick unit of planar-bedded calcarenite, which thickens to the south. These two units represent another phase of beach deposition. The planar-bedded calcarenite is overlain by about 5 m of large-scale, cross-bedded eolian calcarenite. The planar-bedded and cross-bedded calcarenites show extensive development of small- to large-scale rhizoliths.

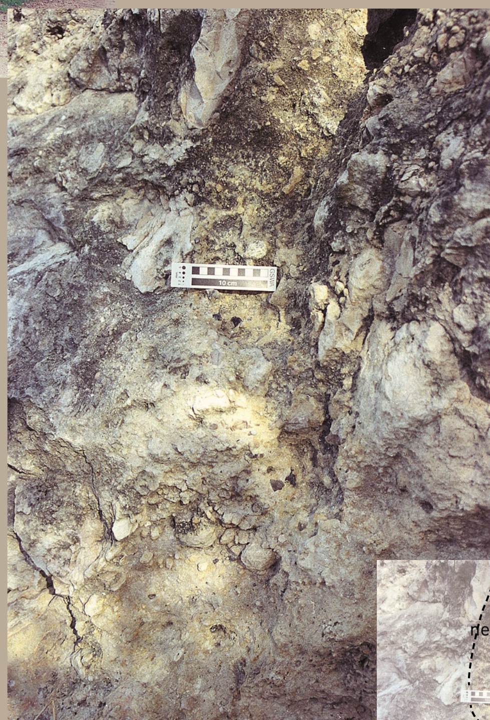
What is the age of these beds?

The molluscan faunas of the upper and lower shell units at Peppermint Grove have been described in detail by Kendrick (1960) and summarized by Playford et al. (1976). Kendrick (1960) considered the marine deposits to be Middle Pleistocene in age, before the last interglacial period, and concluded that they were deposited in a shallow-marine gulf during a period when temperatures were similar to those of today. In contrast, Chalmer et al. (1976) suggested that the marine units were deposited in the seaward part of an estuary with good oceanic exchange.

More recently, studies undertaken to determine absolute ages of the marine units using electron spin resonance (Hewgill et al., 1983) and amino acid racemization (Murray-Wallace and Kimber, 1989) indicate that the upper shell unit was deposited in the second-last interglacial period (**Oxygen Isotope Stage** 7 or penultimate interglacial), between 190 000 and 240 000 years ago. The age of the lower shelly unit is more problematic because of the degree of weathering, and it could have been deposited during the same interglacial period as the upper shell unit (Oxygen

Figure 11.
Brecciated calcrete (left of photo) draping shelly marine units at Peppermint Grove (MGA 384015E 6459345N)





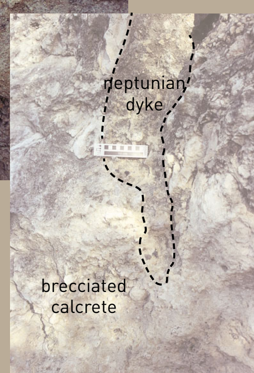


Figure 12.
Brecciated black limestone neptunian dyke at Peppermint Grove (MGA 384015E 6459345N)

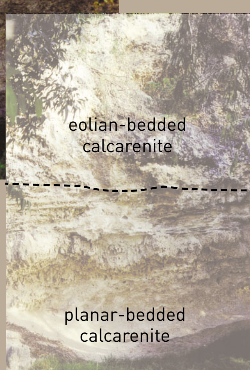


Figure 13.
Thick, planar-bedded, shelly marine calcarenite at Peppermint Grove (MGA 384005E 6459330N)

Isotope Stage 7) or earlier, in the third-last interglacial period, between 300 000 and 340 000 years ago (Oxygen Isotope Stage 9 or ante-penultimate interglacial; Kendrick et al., 1991). These studies have also shown that the marine units at Peppermint Grove are significantly older than those at nearby Minim Cove, which were dated at about 132 000 years old (Szabo, 1979).

Getting there

Roadside parking is available on The Esplanade, south of Forrest Street. From The Esplanade, follow the path north-northeast along the Swan River to the outcrop. Access is unrestricted.

The Coombe

At The Coombe, on the foreshore of the Swan River in Mosman Park (Fig. 9), there is a cliff exposure of marine units (Fig. 14) similar to those at Peppermint Grove. Both sites contain a three-fold shelly marine sequence within a mainly eolian section.

At the base of the section at The Coombe, the lower 0.4 m-thick shelly calcarenite comprises mostly broken shell debris with a few whole shells. This unit is overlain by 3.8 m of large-scale cross-bedded eolian calcarenite. This eolian calcarenite is overlain by a second shelly calcarenite unit, 0.3 m thick, the top of which is about 6 m above river level. Kendrick et al. (1991) described the salient differences in the shelly fauna between these two shell units. Above the upper shell unit, to the top of the section, is a thick development of large-scale cross-bedded eolian calcarenite.

Despite similarities between the sections at The Coombe and Peppermint Grove, there are distinct differences. The eolian calcarenite between the two shell units at The Coombe is absent at Peppermint Grove. Also the lower shelly calcarenite at The Coombe contains shelly debris and a few whole shells, whereas the probable equivalent unit at Peppermint Grove, which lies below the paleosol, lacks **macrofossils** (Kendrick et al., 1991).

Neither of these two main shell units at The Coombe is horizontal, and both rise slightly to the west. As the lower shell unit is traced along the section towards the west, it can be seen to change in character — it contains only a few whole shells in the east, and noticeably more whole, and larger, shells in the west, and these whole shells are smoothed and polished. Also, the number of limestone pebbles at the base of this shell unit increases to the west as the unit merges into a brecciated calcrete.

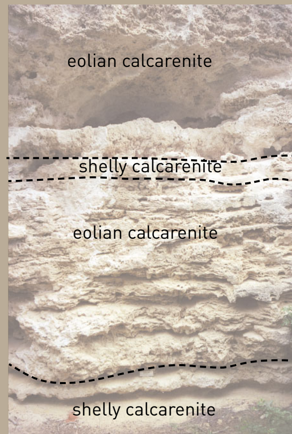


Figure 14.
Shelly, marine calcarenite (at base and near top of photo) in eolian calcarenite at The Coombe (MGA 384385E 6457475N)

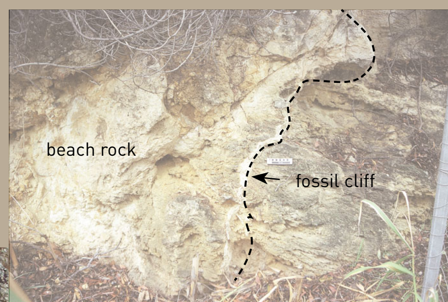


Figure 15.
Beach rock (left of photo) abutting and overriding a low fossil cliff (right of photo) at The Coombe (MGA 384385E 6457475N)

The brecciated calcrete is interpreted as cemented beach rock, and it can be seen to abut an eroded mass of eolian calcarenite (Fig. 15). This rocky mass was undoubtedly a small rocky point or promontory on the beach. On top of this former rocky point is a third discrete shelly calcarenite containing scattered shells similar to those in the basal shelly calcarenite.

The similarities between the marine units at The Coombe and those at Peppermint Grove indicate a close correlation between the two sites in terms of their respective geological histories and environments of deposition. Based on electron spin resonance, Kendrick et al. (1991) concluded that the upper shell unit at The Coombe is the same age as that at Peppermint Grove, deposited in the second-last interglacial period (Oxygen Isotope Stage 7), and conjectured that the lower shell unit was either deposited in the same period or earlier (Oxygen Isotope Stage 9). Thus, the deposits at The Coombe were probably deposited in the same, seaward part of the estuary as the Peppermint Grove rocks.

Getting there

Access to the cliff section is unrestricted, although it is fenced off from the adjoining children's playground. Parking is available on the river foreshore adjacent to the playground at the foot of The Coombe.

Minim Cove

The marine units exposed in the cliff sections along the foreshore of the Swan River west of Point Roe (MGA* 384200E 6456140N) are different from those at Peppermint Grove and The Coombe. The type section for these units — the Minim Cove Member of the Tamala Limestone (Fig. 16) — is best exposed at Minim Cove (Fig. 9), where two richly fossiliferous units lie within a mainly eolian sequence of calcarenites.

At the base of the section is a lower shell unit comprising a basal, 1.1 m-thick, medium-scale, cross-bedded, shelly calcarenite and an overlying, 0.3 m-thick, planar-bedded, richly fossiliferous calcarenite. The shells in both parts of this unit are a diverse assemblage of mainly molluscs with both valves still joined. The orientation of the shells in the lower part suggests deposition in quiet, shallow-marine conditions, whereas the orientation of those in the upper part indicates high-energy current deposition, such as in a beach environment.

* Coordinates quoted in this guide refer to Zone 50 of the Map Grid of Australia (MGA) coordinate system, which is based on the Geodetic Datum of Australia 1994 (GDA94). The coordinate system can also be used with street directories or Global Positioning Systems (GPS) in referencing the localities.

Overlying this richly fossiliferous calcarenite is 0.9 m of large-scale, cross-bedded, eolian calcarenite. Above this, an upper shell unit comprises 0.2 m of planar-bedded, richly fossiliferous calcarenite, followed by 1.1 m of sparsely shelly calcarenite containing some accumulations of shells and shelly debris. The top of this upper shell unit is about 4.5 m above river level.

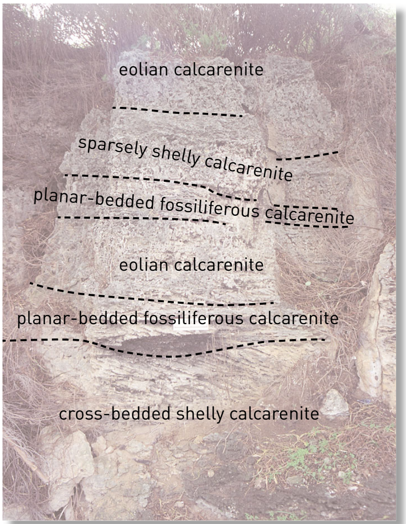


Figure 16.
The section at Minim Cove
(MGA 383470E 6456425N)

Overlying the upper shell bed sequence and extending to the top of the section is a thick sequence of large-scale, cross-bedded, eolian calcarenite, which represents a major dune-building episode that followed the period of marine and shoreline deposition. Solution pipes and small- to large-scale rhizoliths are common throughout the section.

More age correlations

Fairbridge (1953) and Kendrick (1960) correlated the shell beds at Minim Cove with those at Peppermint Grove. However, more recent work by Hewgill et al. (1983), using electron spin resonance, and by Murray-Wallace and Kimber (1989), using **aminostratigraphy**, has shown that the Minim Cove Member is last interglacial in age (Oxygen Isotope Substage 5e). Hewgill et al. (1983) also correlated the Minim Cove Member with the Rottnest Limestone (Playford, 1988) — a coral-reef limestone exposed at Fairbridge Bluff on Rottnest Island — which Szabo (1979), using uranium/thorium dating techniques, determined to be 132 000 ± 5000 years old.

Getting there

Access to the cliff section at Minim Cove is unrestricted. Street parking is available on Fairbairn Street near the entrance to the Minim Cove Park. From the park entrance follow the concrete footpath to the west towards the overhead power lines. There is a steep flight of steps down to the Minim Cove foreshore, 25 m west of the power lines.

Mudurup Rocks

On the foreshore and in the cliffs at Mudurup Rocks at Cottesloe (Fig. 9) is a sequence of beach and **prograding shoreline** deposits (Fig. 17).

Exposed on the beach is a development of thick beach rock that extends from below water level to the high-tide mark. The beach rock contains large broken shells of **gastropods** and other molluscs and some coral fragments set in a hard, cemented shelly matrix.

Within the beach rock are numerous rhizoliths, ranging in size from 1 cm to over 1 m in diameter. These rhizoliths are calcified fossil root structures that have developed through the precipitation of calcium carbonate around the roots

Figure 17.
The section at Mudurup Rocks (MGA 382065E 6459035N). Beach rock (foreground) is overlain by cross-bedded and planar-bedded shelly marine calcarenite, which in turn is overlain by eolian calcarenite

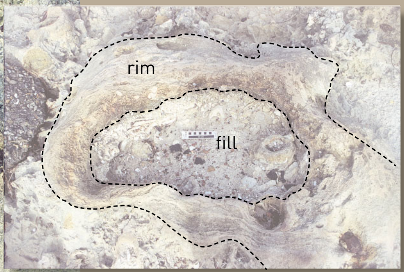


Figure 18.
Large rhizolith filled with beach material at Mudurup Rocks (MGA 382065E 6459035N)

Figure 19.
Thin, shelly, marine calcarenite in eolian calcarenite at Hinemoa Rock (MGA 384765E 6457215N)

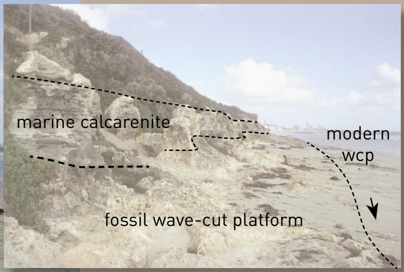


Figure 20.
Shelly, marine calcarenite on the wave-cut platform (wcp) below the Vlamingh Memorial, Cottesloe (MGA 382090E 6457190N)

of shrubs and trees growing on the original dunes. Following death and decay of the roots, the resulting cavity was filled with limestone and **carbonate** cement. Most of the rhizoliths still show the typical rimming by thin layers of calcrete growing in to the core, and many are partially filled with shelly calcarenite, broken limestone debris, and large broken shells and coral fragments, which were probably deposited on a beach that at one time blanketed the beach rock (Fig. 18). This indicates that since the development of the beach rock there was a period of subaerial weathering, during which the rhizoliths were formed, and this was followed by the re-establishment of shallow-marine or beach conditions, which led to the infilling of the rhizoliths. At some later stage, coastal erosion and tidal action uncovered the beach rock, exposing and partially excavating the rhizoliths and their contents.

The shallow-marine and beach deposits that filled the rhizoliths in the beach rock can be clearly seen in the cliff section at Mudurup Rocks (Fig. 17). Shallow-marine conditions are represented by the 0.6 m of fine-grained, cross-bedded, shelly calcarenite that unconformably overlies the beach rock, and overlying this is 2.6 m of planar-bedded, coarse-grained, shelly calcarenite with shell and coral fragments, which indicate deposition on a beach. This is unconformably overlain by 2.7 m of typically large-scale, cross-bedded, eolian calcarenite, which represents a return to dune building.

Numerous small- and large-scale rhizoliths have developed throughout the upper, eolian, part of the cliff section.

Getting there

Access to the beach at Mudurup Rocks is unrestricted. Parking is available in the public car park on Marine Parade at Mudurup Rocks, immediately south of the Cottesloe beach groyne. From the car park, a steep flight of concrete steps descends to the beach.

Other localities

Marine shell beds similar to those at the sites described above can be seen at three other localities in the Cottesloe – Mosman Park area: Hinemoa Rock, Vlamingh Memorial, and Beach Street (Fig. 9). There is also a fossil **wave-cut platform** and cliff along Blackwall Reach (Fig. 9).

At Hinemoa Rock near Chidley Point there is a 15 cm-thick, planar-bedded, shelly calcarenite within large-scale, cross-bedded eolian calcarenite about 5 m above river level (Fig. 19). It is very similar in appearance to the shell beds

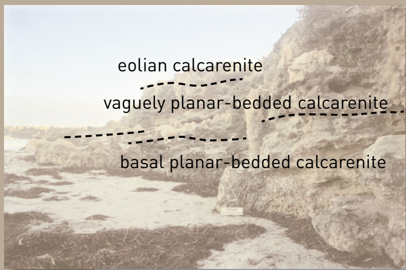
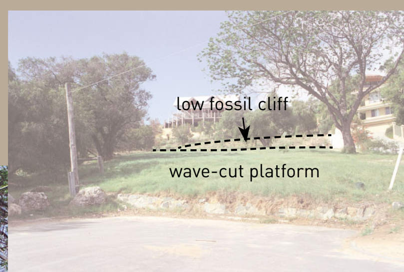


Figure 21.
Shelly, marine calcarenite at the base of cliffs south of the Beach Street groyne, Cottesloe (MGA 382090E 6458000N)

Figure 22.
General view of the wave-cut platform and low fossil cliff at Blackwall Reach Parade, Bicton (MGA 385135E 6456575N)

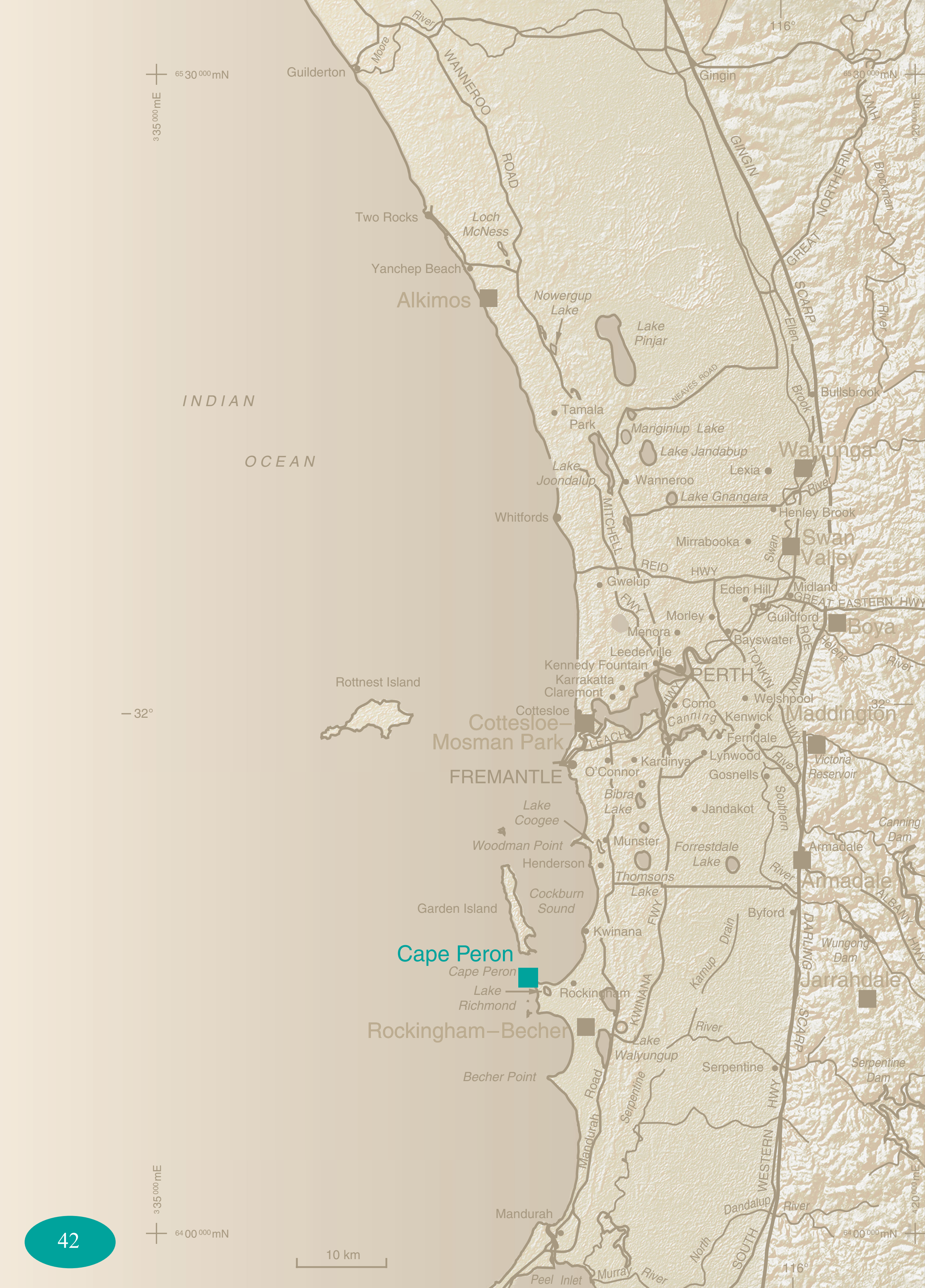


at Minim Cove, and a similar height above river level to the upper shell bed at Minim Cove.

Below the Vlamingh Memorial on the Cottesloe foreshore, 0.9 m of shelly calcarenite, deposited in a beach environment, rests disconformably on a wave-cut platform (Fig. 20). The contained shells are mainly gastropods and bivalve molluscs, but also include some fragments of colonial coral. The wave-cut platform on which the shell bed lies is slightly higher than the present-day wave-cut platform, indicating that the older wave-cut platform is being uncovered and planed down to modern levels by present-day coastal processes.

On the foreshore at Cottesloe, immediately south of the Beach Street groyne, there is a similar exposure to that at the Vlamingh Memorial location. Here, 2.6 m of shelly calcarenite is developed on a wave-cut platform and is overlain by typically large-scale, cross-bedded, eolian calcarenite (Fig. 21). The shelly calcarenite comprises a basal 1.1 m of planar-bedded, extremely fossiliferous calcarenite, with the number and size of shells decreasing up the profile. The attitude of the shells indicates deposition in a current. Above this are 1.5 m of vaguely planar-bedded, shelly calcarenite composed mostly of broken shell debris, but with locally thin, discrete shell bands containing larger, though still broken, gastropod and other mollusc shells. This shell bed is interpreted as a beach deposit. The rhizoliths in the wave-cut platform are analogous to those seen at Mudurup Rocks.

On the southern bank of the Swan River along Blackwall Reach, at the northern end of Blackwall Reach Parade in Bicton, a wave-cut platform rises from 6 to11 m above the level of the Swan River (Fig. 22). A low fossil cliff cut in typical eolian calcarenite backs the wave-cut platform. Overlying the wave-cut platform, at the base of the fossil cliff, is about 0.6 m of shelly grit composed mostly of broken shell debris in a sandy matrix. The shell grit is beach material deposited on the wave-cut platform at the foot of the fossil cliff.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NORTHERN
HWY
Brockman
River
Two Rocks
Loch
McNess
Yanchep Beach
Alkimos
Nowergup
Lake
Lake
Pinjar
Ellen
Brook
SCARP
NEAVES ROAD
Bullsbrook
INDIAN
OCEAN
Tamala
Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lexia
Lake
Joondalup
Wanneroo
Lake Gnangara
Henley Brook
Whitfords
MITCHELL
Mirrabooka
Swan
Valley
REID
HWY
Gwelup
FWY
Eden Hill
Midland
GREAT EASTERN HWY
Morley
Guildford
Boya
Menora
Bayswater
ROE
Helena
River
Leederville
TONKIN
Kennedy Fountain
PERTH
Karrakatta
Claremont
HWY
Rottnest Island
32°
Cottesloe
Como
Welshpool
Maddington
Cottesloe–
Mosman Park
Canning
Kenwick
LEACH
Ferndale
Kardinya
Lynwood
Victoria
Reservoir
FREMANTLE
O'Connor
Gosnells
Bibra
Lake
Lake
Coogee
Jandakot
Southern
Canning
Dam
Munster
Woodman Point
Forrestdale
Lake
Armadale
Henderson
Thomsons
Lake
Armadale
ALBANY
Cockburn
Sound
Garden Island
Byford
Kwinana
Drain
Wungong
Dam
DARLING
Cape Peron
Cape Peron
Jarrahdale
Lake
Richmond
Rockingham
KWINANA
Karnup
Rockingham–Becher
River
Lake
Walyungup
Serpentine
Serpentine
Dam
Becher Point
Road
Serpentine
Mandurah
WESTERN
Dandalup
Mandurah
64 00 000 mN
North
SOUTH
10 km
Peel Inlet
Murray
River
116°

CAPE PERON

The rocky headland of Cape Peron was once an offshore island that has been joined to the mainland by the progressive build-up of sand spits and beach ridges

Figure 23. Cape Peron area

The isolated rocky headland of Cape Peron (Fig. 23) was formerly an offshore island similar to present-day Penguin Island and Carnac Island, and developed into a **tombolo** by the gradual development of sand spits and a prograding, sandy, **cuspate beach-ridge plain** building out from the mainland in a westerly direction. Similar sand spits can be seen connecting Bird Island, Seal Island, and Penguin Island to the mainland (nicely illustrated in the aerial photo mosaic of Rockingham–Becher in Figure 32). However, it is the coastal landform features of Cape Peron that are of most interest, including **paleosols**, **karstic** features, **beach rock**, **raised beaches**, and elevated shoreline platforms.

Fairbridge (1950) described in detail the geology and geomorphology of Cape Peron, and through his work Cape Peron has become a site of global significance in studying worldwide (eustatic) changes in sea level (Fairbridge, 1961). Later studies include that of Passmore (1967).

Cape Peron is composed of Tamala Limestone, overlain by dune sand of the Quindalup Dune System. Here the Tamala Limestone is all large-scale cross-bedded, indicative of eolian origin, and no marine nearshore or foreshore deposits have been recognized within the eolian sequence.

The Quindalup Dune System comprises two main morphological units. The first, which blankets much of the Tamala Limestone, is a complex pattern of irregular, hummocky dunes. They have developed as imperfect **parabolic dunes** because of the nature of the topography of Cape Peron and the restricted area over which they have been able to form. The second morphological unit to the southeast of Cape Peron is a series of numerous parallel beach ridges that follows the line of Shoalwater Bay. These beach ridges form part of the cuspate beach-ridge plain that links the former island of Cape Peron to the mainland.

Over most of Cape Peron, variably thick, hard **calcrete** layers can be seen both within and on top of the Tamala Limestone. These calcrete layers are called **pedogenic calcretes** (Goudie, 1983), and they formed when groundwater, rich in dissolved calcium carbonate, rose to the surface or near-surface zones of the dune through capillary action. The dissolved calcium carbonate was deposited below the original surface of the dunes during evaporation, or other soil-forming (pedogenic) processes. Immediately below the layers of pedogenic calcrete, where the calcium carbonate was removed in solution by the groundwater, the Tamala Limestone is very soft and friable.

On the north side of Fishermans Head (Fig. 23) the pedogenic calcrete is overlain by a patchy development of thin, grey to brown fossil soil (Fig. 24) with a veneer of grey, laminated calcrete. Normally fossil soils such as these contain land snails (*Bothriembryon*) and weevil pupal cases (*Leptopius*), as, for example, on Rottnest Island (Playford, 1988), but none are found at Cape Peron.

Figure 24.
Thin, brown paleosol (fossil soil) over calcrete at Fishermans Head, Cape Peron (MGA 376215E 6429335N)

Figure 25.
Large- and small-scale rhizoliths at Point Peron, Cape Peron (MGA 376310E 6428740N)

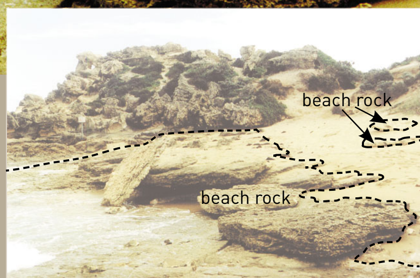


Figure 26.
Planar-bedded beach rock at Point Peron, Cape Peron (MGA 376285E 6428740N)

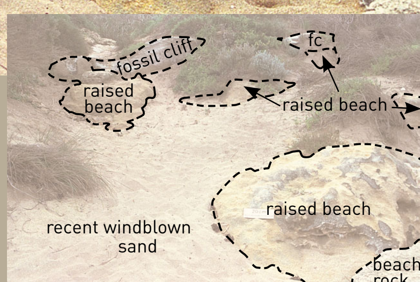


Figure 27.
Raised beach partly overlain by more-recent wind-blown sand at Point Peron, Cape Peron (MGA 376290E 6428755N)

Within the pedogenic calcrete layers and underlying friable **calcarenite** are abundant **rhizoliths** (Fig. 25). Prominent within the zone of rhizolith development are large, nominally cylindrical structures, many of which reach 1 m in diameter and several metres in height (Fig. 25). Fairbridge (1950) thought that these structures were solution pipes, such as **sinkholes** and **swallets**, which developed in depressions in the calcarenite through the dissolution of carbonate. However, they are now believed to have formed in the same way as the rhizoliths, except that they formed around the taproots of large trees. The outside of the structures is strongly cemented and shows the typical development of thin layers of calcrete, whereas the inside is commonly **carbonate** sand, which filled the void left by the decaying root. These large-scale features are located 35 m west of the rocky headland at the western end of Haliotis Bay and on the south side of Fishermans Head.

Within some of the larger rhizoliths at Fishermans Head, and notably close to the walls, there are roughly ellipsoidal, hollow casts 2 to 5 cm long and 1 to 2 cm in diameter. These have been interpreted as fossil larval casts of a weevil (*Leptopius*) (Fairbridge, 1950); alternatively, they could be the brood cells of solitary native bees.

On the beaches at Haliotis Bay and Long Reach (Fig. 23) are thick exposures of beach rock. At both locations the beach rock extends from below water level to the high-tide mark. Although it appears to be within the current tidal range, the beach rock is probably not a contemporary deposit because it extends through a vertical range of at least 3 m. The current tidal range at Cape Peron should not, theoretically, allow the development of more than about 1.5 m of beach rock (Fairbridge, 1950), and therefore it probably formed during a period of changing sea levels.

On the foreshore on the southern side of Point Peron (Fig. 23) there is a planar-bedded, highly fossiliferous calcarenite that dips seawards at 3° (Fig. 26), and reaches to about 4.5 m above sea level. The deposit comprises tightly packed, disarticulated and broken shells of **molluscs,** including **gastropods**, up to 10 mm in size, set in a hard, cemented, shelly matrix of broken shell debris. Fairbridge (1950) described the contained fauna in detail. The sorting of the shells by wave action is evident in the coarser and finer bands alternating throughout the material, indicating that it was deposited in a beach environment when the sea level was about 4.5 m higher than it is today. Based on eustatic sea-level changes, Fairbridge (1961) determined that this fossil beach deposit is 5120 years old.

Also at Point Peron there is a conspicuous raised beach at two localities. At both localities the raised beach rises from about 4.5 m to about 7 m above the high-tide mark and is seen plastered on the fossil beach described above and against a low fossil cliff capped by pedogenic calcrete (Fig. 27).

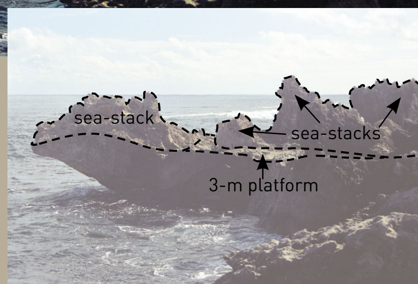


Figure 28.
Upper level (3 m) shoreline platform with sea stacks at Fishermans Head, Cape Peron (MGA 376135E 6429315N)

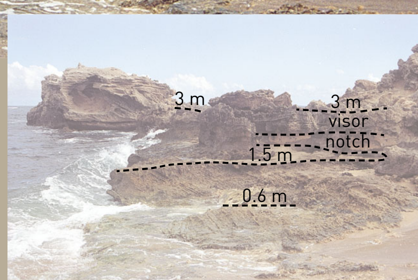


Figure 29.
Low-level (0.6 m) shoreline platform (centre foreground), intermediate-level (1.5 m) shoreline platform (centre mid-ground) cutting into the edge of the upper level (3 m) platform with a well-developed notch and visor at Point Peron, Cape Peron (MGA 376285E 6428740N)

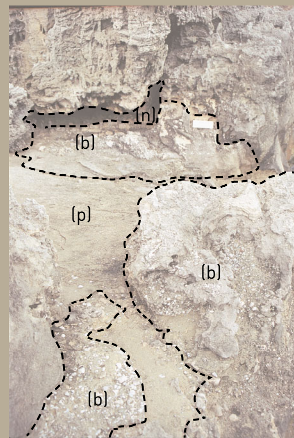


*Figure 30.
Remnant beach deposits (b) coating the intermediate-level (1.5 m) shoreline platform (p) and notch (n) at Fishermans Head, Cape Peron (MGA 376175E 6429295N)*

Without doubt, the most obvious of the features around the coast of Cape Peron are the elevated shoreline platforms. The shoreline platforms are horizontal surfaces that have been formed along the shore by wave erosion during periods of higher sea level. Associated with the elevated shoreline platforms are blowholes, cliffs, and **notches**. Three levels of elevated shoreline platforms can be recognized: an upper level at about 3 m; an intermediate level at about 1.5 m; and a lower level at about 0.6 m above the modern shoreline platform. The elevation of the modern platform around Cape Peron is just a few centimetres below the level of low-water spring tides (Fairbridge, 1950).

The upper level platform is the most prominent of the elevated shoreline platforms, and is extensively preserved around Cape Peron — notably at Fishermans Head (Fig. 28) and for 190 m south of Fishermans Head, on both sides of Point Peron, and between Point Peron and Haliotis Bay. At Fishermans Head and Point Peron there are a number of former **sea stacks** preserved on the upper level platform that rise almost vertically for about 3 m. Considering they were formed by wave erosion when the shoreline was at this level, they are remarkably fresh-looking.

The intermediate-level platform is not as extensive as the upper level, principally because it is within the zone of wave action and is therefore more prone to erosion. Nevertheless, it is well preserved north and south of Fishermans Head, on both sides of Point Peron, and on both sides of Haliotis Bay. The best-preserved examples of the intermediate-level platform are at Point Peron, where it cuts into the edge of the upper level platform with a well-developed notch (Fig. 29). Fishermans Head is the only locality where beach deposits associated with the intermediate-level platform have been found — a remnant deposit of shelly calcarenite coating the intermediate-level platform and notch (Fig. 30).

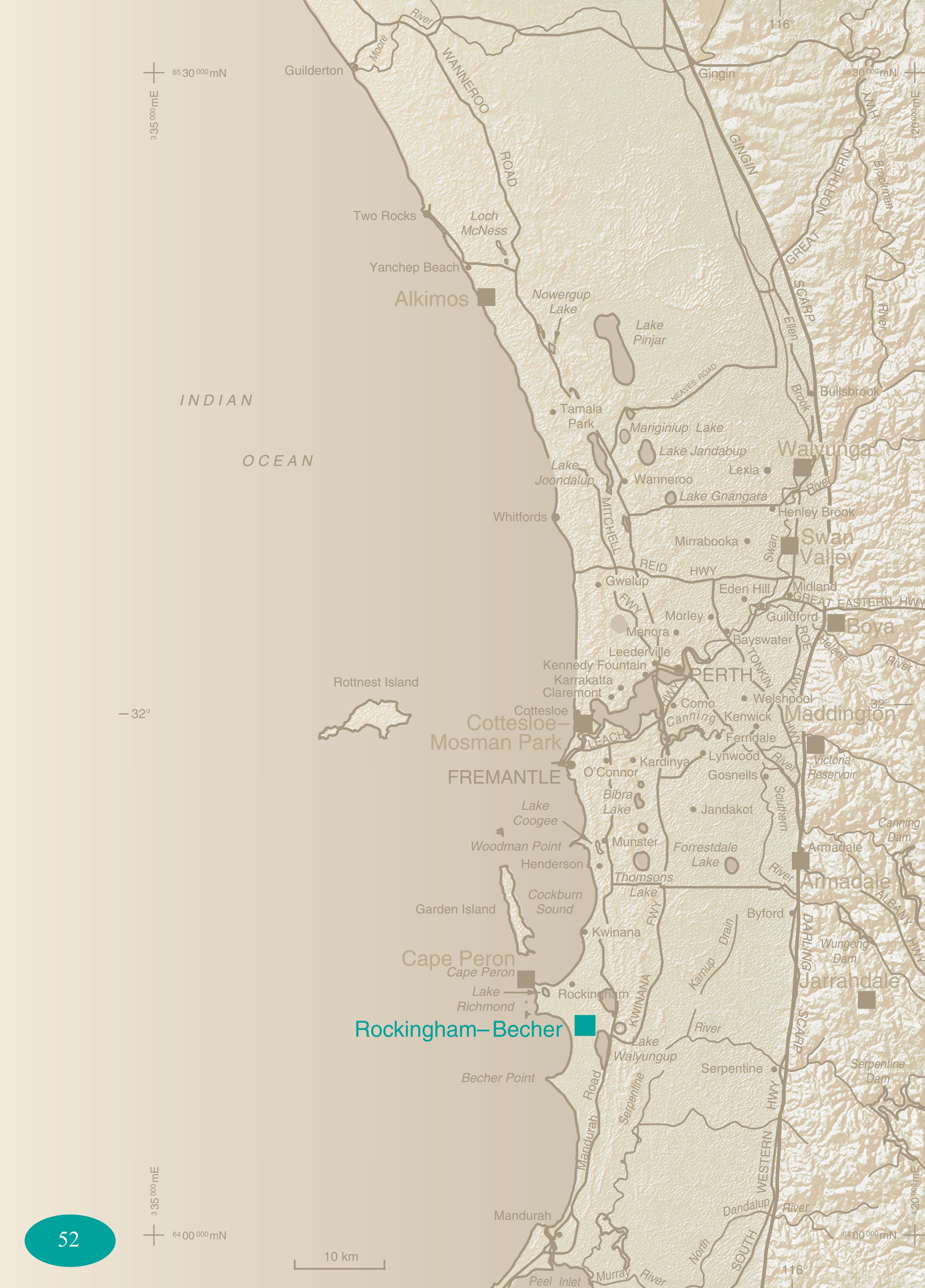
The lower level (0.6 m) platform is only found in very sheltered positions such as on the west side of Haliotis Bay and on both sides of Point Peron (Fig. 29). Although it is well within the modern **swash zone**, where seen, the lower level is clearly higher than the modern shoreline platform.

Getting there

Access to the Cape Peron peninsula is unrestricted. Car parking is available in two public car parks at the terminus of Point Peron Road (Fig. 23). Several well-formed tracks cross the peninsula and lead to many of the promontory and foreshore exposures.

Drop in sea level leaves shoreline platforms high and dry

Playford (1988) described three levels of elevated shoreline platforms on Rottnest Island, at 2.4 m, 1.1 m, and 0.5 m above the elevation of the modern platform. Given that both Cape Peron and Rottnest Island have similar geomorphological settings, and the similar elevation of these ancient shorelines, it is tempting to immediately correlate the three levels at Cape Peron with the three levels on Rottnest Island. However, there is a large contrast in the evidence from these two locations. Fairbridge (1950) considered that the upper level platform at Cape Peron is the oldest of the three levels, and that the intermediate and lower levels represent successive still-stands as sea level fell, from the post-glacial high, to its present level. However, Playford (1988) clearly showed the lower level platform on Rottnest Island to be the oldest, and the upper level platform to be the youngest, forming about 4800 to 5900 years ago. He also demonstrated that the three levels on Rottnest Island were formed towards the end of the post-glacial rise in sea level. Absolute dating of the elevated shoreline platforms at Cape Peron has been problematic, but on geomorphological evidence, Fairbridge (1950) showed a relationship between the upper level platform and the fossil-beach deposit at Point Peron, and used the age of this beach deposit (5120 years old) as evidence of the age of the upper level platform (Fairbridge, 1961). This date is similar to that for the upper level platform on Rottnest Island. However, the well-documented and well-dated evidence from Rottnest Island appears to throw into doubt some of the conclusions of Fairbridge (1950, 1961) regarding the relative and absolute ages of the lower two elevated shoreline platforms on Cape Peron.



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HWY
Brockman
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Two Rocks
Loch
McNess
Yanchep Beach
Alkimos
Nowergup
Lake
Lake
Pinjar
SCARP
Ellen
Brook
NEAVES ROAD
Bullsbrook
Tamala
Park
Mariginiup
Lake
Lake Jandabup
Walyunga
Lexia
Lake
Joondalup
Wanneroo
River
Lake Gnangara
Henley Brook
Whitfords
MITCHELL
Mirrabooka
Swan
Swan
Valley
REID
HWY
Gwelup
FWY
Eden Hill
Midland
GREAT
EASTERN
HWY
Morley
Guildford
Menora
Boya
Bayswater
ROE
Helena
River
Leederville
Kennedy Fountain
TONKIN
Karrakatta
PERTH
Claremont
HWY
Rottnest Island
Welshpool
Como
Cottesloe
Canning
Kenwick
Maddington
Cottesloe–
Mosman Park
LEACH
Ferndale
Kardinya
Lynwood
River
Victoria
Reservoir
FREMANTLE
O'Connor
Gosnells
Bibra
Lake
Jandakot
Southern
Lake
Coogee
Canning
Dam
Woodman Point
Munster
Forrestdale
Lake
Armadale
Henderson
Thomsons
Lake
River
Armadale
ALBANY
Cockburn
Sound
FWY
Byford
Garden Island
Drain
DARLING
Kwinana
Wungong
Dam
HWY
Cape Peron
Cape Peron
Jarrahdale
Lake
Richmond
Rockingham
KWINANA
Karnup
Rockingham–Becher
River
Lake
Walyungup
SCARP
Becher Point
Serpentine
Serpentine
Dam
Road
Serpentine
HWY
Mandurah
WESTERN
Mandurah
Dandalup
River
North
SOUTH
Peel Inlet
Murray
River
10 km
116°
32°
65 30 000 mN
64 00 000 mN
3 35 000 mE
4 20 000 mE

ROCKINGHAM–BECHER

This large plain is composed of many parallel north-trending sand ridges, each marking the position of a former shoreline

The westerly extension of the Rockingham–Becher plain

South of the Swan River the most obvious landforms along the coast are the large, low, undulating plains that extend beyond the general trend of the coast at Woodman Point and between Kwinana and Mandurah. These plains are composed of loose to weakly cemented calcareous sands of the Holocene Safety Bay Sand (Passmore, 1970; Playford and Low, 1972), and are one of the many geomorphological units of the Quindalup Dune System.

The plain between Kwinana and Mandurah is known as the Rockingham–Becher Plain. It is by far the largest of the plains along the coast of the Perth Region, being some 40 km long and up to 10 km wide, bound by north-northeasterly trending dunes of the Spearwood Dune System to the east, and

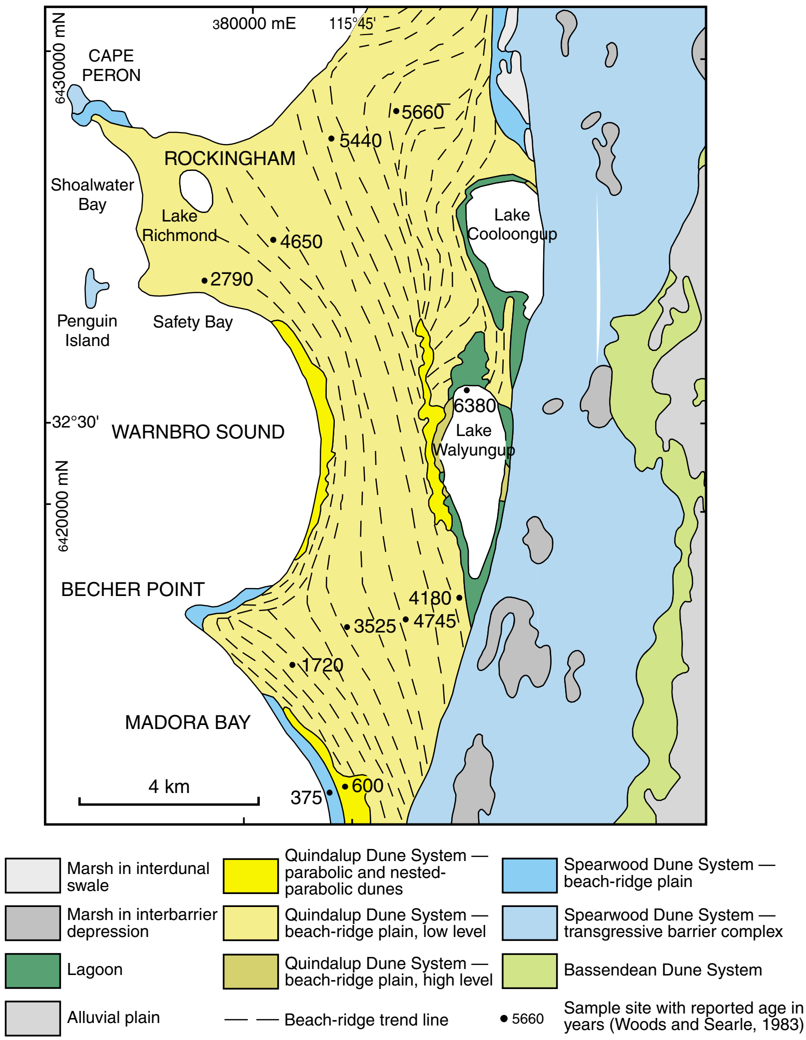


Figure 31.
The Rockingham–Becher Plain showing the trend of the beach ridges and the location of radiocarbon sample sites

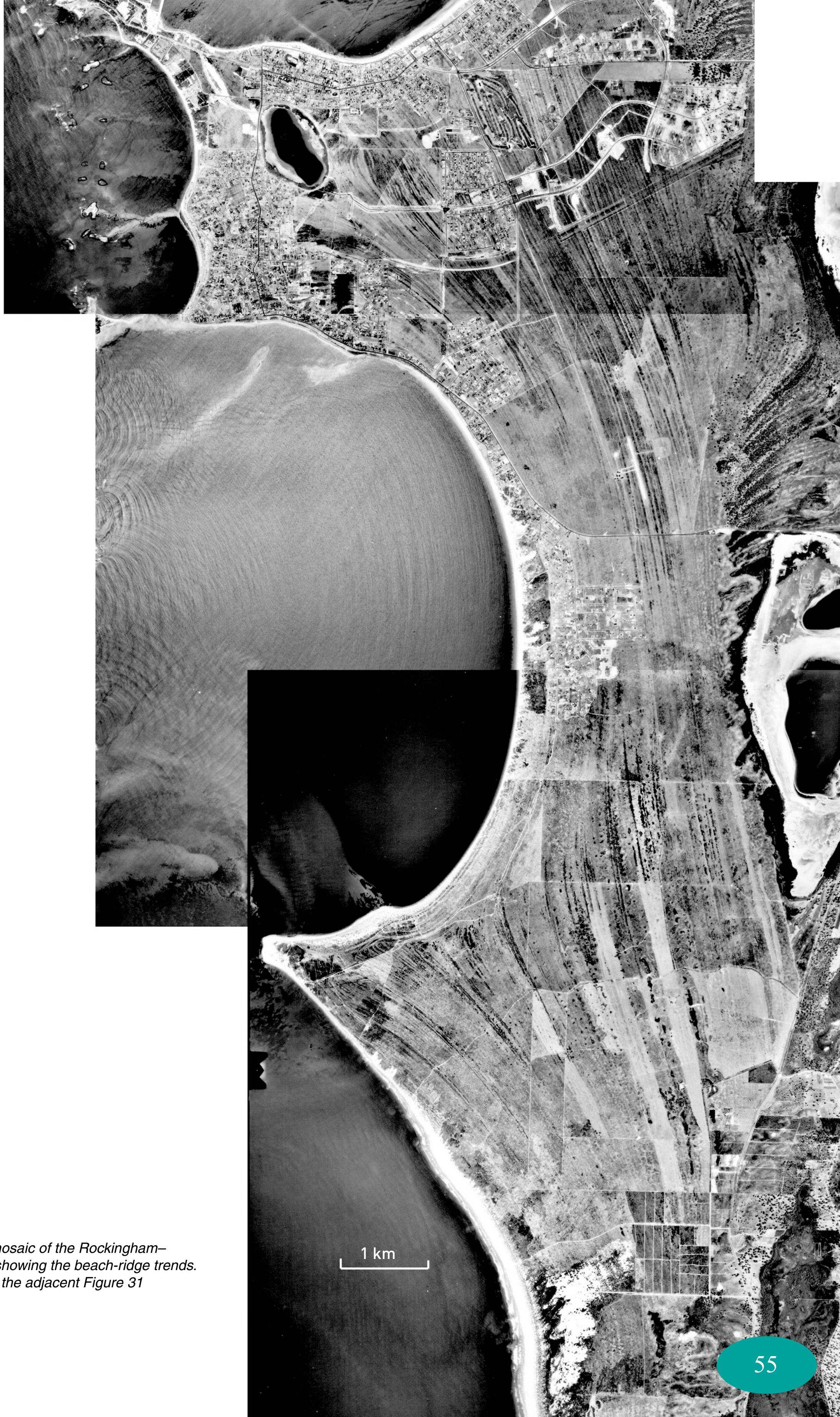


Figure 32.
Aerial photo mosaic of the Rockingham–Becher Plain showing the beach-ridge trends. Compare with the adjacent Figure 31

the Indian Ocean to the west. The plain is the surface expression of a pile of Pleistocene and Holocene sedimentary rocks that fill what was once a marine basin (Searle et al., 1988). The **stratigraphy** of the sedimentary rocks underlying the plain is fairly simple, comprising three main units, each of which represents a distinct environment of deposition — basin **carbonate** muds of the Bridport Calcilutite (Semeniuk and Searle, 1987), submarine sand banks of the Becher Sand (Semeniuk and Searle, 1985), and beaches and **beach ridges** of the Safety Bay Sand (Passmore, 1970; Playford and Low, 1972).

The Rockingham–Becher Plain is irregular in shape and is formed by the coalescing of two asymmetric, triangular-shaped beach-ridge plains that have built out westwards from the line of the Spearwood dunes (Figs 31, 32). These types of terrain have been called cuspate forelands (Bird, 1984), accretionary cusps (Semeniuk and Searle, 1986), or **cuspate beach-ridge plains** (Semeniuk et al., 1989). As its form suggests, the plain is composed of numerous parallel ridges. The ridges are lower than is typical of dunes, rarely exceeding 5 m in height, and do not show the cross-bedding typical of dunes. Each ridge is an individual **foredune** (Bird, 1984) that has been built up by **eolian** activity as a low ridge at the back of a beach, but seaward of the higher relief dune complexes immediately inland. As such, they indicate a former position of the shoreline — many of which are easily recognizable in Figure 32.

Passmore (1967), Seddon (1972), and Searle et al. (1988) provided detailed descriptions of the morphology of the plain, in which there are three generalized patterns of beach ridges. Firstly, there is the series of regularly spaced beach ridges that, for the most part, are seldom more than 5 m higher than the intervening swales. The distances between the crests of individual beach ridges ranges from 50 to 100 m. Their regular spacing and low relief suggest formation as the plain was being built seawards. Secondly, there are beach ridges with reliefs between 6 and 10 m (although some have been noted over 20 m in relief), apparently regularly interspersed within the low-relief beach ridges. These probably represent a slowing down in the growth of the beach-ridge plain, thereby allowing more time for the development of the beach ridges, albeit also at regular intervals. Thirdly, there are complex patterns of beach ridges, particularly at the apices of the two triangular-shaped beach-ridge plains that make up the Rockingham–Becher Plain.

The Rockingham–Becher Plain has been studied in some detail and the results used to determine not only the mid- to late-Holocene depositional history of the plain, but also the sea-level history of this part of the Western Australian coast (Searle et al., 1988; Searle and Woods, 1986; Semeniuk, 1986; Semeniuk and Searle, 1985, 1987; Semeniuk et al., 1988, 1989; Woods and Searle, 1983). The sequence of events that took place as the beach-ridge plain gradually built out towards the west from the line of Spearwood dunes is clearly recorded in the layout of successive beach ridges (Fig. 31).

The oldest beach ridges, which are between Lake Cooloongup and Lake Walyungup, formed parallel to the original shoreline at the foot of the Spearwood dunes at a time when sea level was about 2.5 m higher than it is today (Searle and Woods, 1986). Lake Cooloongup truncates these oldest beach ridges, which is evidence that it is younger. The presence of a small fish of a marine to estuarine species in the lake (Passmore, 1967) indicates that sea level must have risen again for a short period after the development of the oldest beach ridges, and when the sea level fell again, Lake Cooloongup was probably isolated as a marine lagoon.

The trend lines of succeeding beach ridges north of Lake Walyungup and north and west of Lake Cooloongup show a complex pattern resulting from continual changes in the direction of offshore currents followed by a period of erosion. Initially **longshore currents** appear to have been dominant, as shown by the northward movement of sediment. But the complex pattern suggests that offshore reefs and islands, probably of Tamala Limestone, had a marked effect on the direction of the currents. The beach-ridge trend lines show the development of a beach-ridge plain building out to the northwest of both lakes, towards the coast at East Rockingham, but erosion truncated this beach-ridge plain as the main focus of formation changed towards Cape Peron and the islands to its south. This is most evident immediately northwest of Lake Walyungup, where the northwest-facing beach-ridge trend lines are truncated to the west by a younger series of west-facing beach ridges (Figs 31, 32). Lake Walyungup may have been formed at this time by the eventual isolation of a marine lagoon.

Successive beach ridges indicate a period of continuous building and development of a bicuspate beach-ridge plain as it built out towards Cape Peron in the north to form a **tombolo**, and across shallow-marine sedimentary rocks in the south at Becher Point towards the offshore reefs of the Five-Fathom Bank (some 7 km offshore). During the development of the Cape Peron tombolo, a former marine inlet was cut off from the ocean by the developing beach ridges to form Lake Richmond. The depth of Lake Richmond (45 m) and the presence of sea shells around its shore are clear testimony to its marine origin.

The construction of the types of beach ridges that form the Rockingham–Becher Plain has all but ceased. Dune building has replaced beach-ridge formation, and high, irregularly shaped and **parabolic dunes** now form along the coast of Shoalwater Bay, Warnbro Sound, and Madora Bay (Fig. 31). The cessation of beach-ridge development is probably the result of diminishing sand supplies from offshore areas, and therefore the increasing relative importance of locally generated longshore currents. This has led to increasing erosion of the foredunes, particularly on southern beaches. There has been some recent inland movement of sand to form dunes and some transportation of sand to the northern beaches, where it was deposited as low beach ridges, for example, north of Becher Point and at Cape Peron.

The cyclic nature of offshore sediment supply is amply illustrated by Fairbridge (1950), who referred to historical records that showed that Safety Bay (formerly called Peel Harbour) was once cut off from Warnbro Sound and protected from southern gales by a series of submerged and emerged sand spits. Within 10 years the spits had disappeared.

The age of the Rockingham–Becher Plain has been determined by radiocarbon dating of shell material from shelly beach layers within the sedimentary rocks below the beach ridges (Searle and Woods, 1986; Searle et al., 1988; Woods and Searle, 1983). Some of the sample sites with reported ages are shown in Figure 31. The results indicated that the whole of the sediment pile below the plain — Bridport Calcilutite, Becher Sand, and Safety Bay Sand — is Holocene in age, and that 7980 years ago, during the post-glacial rise in sea level, the shoreline had reached the Spearwood dunes.

Because the beach ridges mark successive shoreline positions they can be used effectively as isochrons or time planes. The results of the radiocarbon dating show that formation of the beach-ridge plain commenced around 6500 years ago and progressed relatively rapidly. Near Rockingham, construction ceased around 2700 years ago, but it continued at Becher Point until relatively recently.

Getting there

Much of the Rockingham–Becher Plain has been encroached on by urbanization between Rockingham and Port Kennedy, and between Secret Harbour and Mandurah. Only those areas between Port Kennedy and Secret Harbour, and east of Ennis Avenue, have escaped urbanization. The area between Port Kennedy and Secret Harbour is closed to the public because it was once a military firing range and the area potentially contains many unexploded munitions. However, a scientific park has been created near Becher Point in an attempt to preserve some of the features of the plain.

A higher sea level than today?

From the radiocarbon data and sea-level indicators in the measured sections, Searle and Woods (1986) and Searle et al. (1988) were also able to construct a sea-level history for the Rockingham–Becher Plain. They show that 6645 years ago the Holocene sea level reached an elevation of 2.5 m above mean sea level, and that sea level fell gradually to its present level just short of 1000 years ago, where it has remained since. Although this reconstructed sea-level curve is in general agreement with previous studies in this region (Fairbridge, 1961; Playford, 1988), there are some significant differences. For example, no evidence was found for a 3-m drop in sea level, 4700 to 4300 years ago, between the Older and Younger Peron Submergences of Fairbridge (1961, 1976), or for the Younger Peron Submergence itself (4300 to 3200 years ago). Nor was any evidence found for a 1.1-m submergence between 3100 and 2200 years ago, when the upper part of the Herschell Limestone was deposited on Rottnest Island (Playford, 1988).

Clearly, while there is no doubt regarding the existence of changes of sea level throughout the Quaternary, there does appear to be disagreement as to the magnitude of oscillations during this time and the causes of those oscillations. Nonetheless, the history preserved in the Rockingham–Becher Plain is important in helping to unravel the geological and sea-level histories of this part of Western Australia.

Housing is encroaching on the Rockingham–Becher plain

Moore River
Guilderton
WANNEROO ROAD
Gingin
GINGIN
116°
65 30 000 mN
3 35 000 mE
4 20 000 mE
GREAT NORTHERN HWY
Brockman River
Two Rocks
Loch McNess
Yanchep Beach
Alkimos
Nowergup Lake
Lake Pinjar
SCARP
Ellen Brook
NEAVES ROAD
Bullsbrook
INDIAN
OCEAN
Tamala Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lexia
Lake Joondalup
Wanneroo
Lake Gnangara
River
Henley Brook
Whitfords
MITCHELL FWY
Mirrabooka
Swan
Swan Valley
REID HWY
Gwelup
Eden Hill
Midland
GREAT EASTERN HWY
Morley
Guildford
Boya
Menora
Bayswater
ROE HWY
Helena River
Leederville
TONKIN HWY
Kennedy Fountain
PERTH
Karrakatta
Rottnest Island
Claremont
Welshpool
32°
Cottesloe
Como
Canning
Kenwick
Maddington
Cottesloe–Mosman Park
LEACH
Ferndale
Lynwood
Victoria Reservoir
Kardinya
FREMANTLE
O'Connor
Gosnells
Bibra Lake
Jandakot
Southern River
Lake Coogee
Canning Dam
Woodman Point
Munster
Forrestdale Lake
Armadale
Henderson
Thomsons Lake
Armadale
Cockburn Sound
ALBANY HWY
Garden Island
Byford
Kwinana
FWY
Drain
Wungong Dam
DARLING SCARP
Cape Peron
Karnup
Jarrahdale
Lake Richmond
Rockingham
KWINANA
Rockingham–Becher
River
Lake Walyungup
Serpentine
Serpentine Dam
Becher Point
Road
Serpentine
HWY
Mandurah
WESTERN
Dandalup
River
64 00 000 mN
10 km
North
SOUTH
Murray River
Peel Inlet

JARRAHDALE

Visit the railway cutting at Jarrahdale to view the development of thick lateritic profiles over different types of rocks

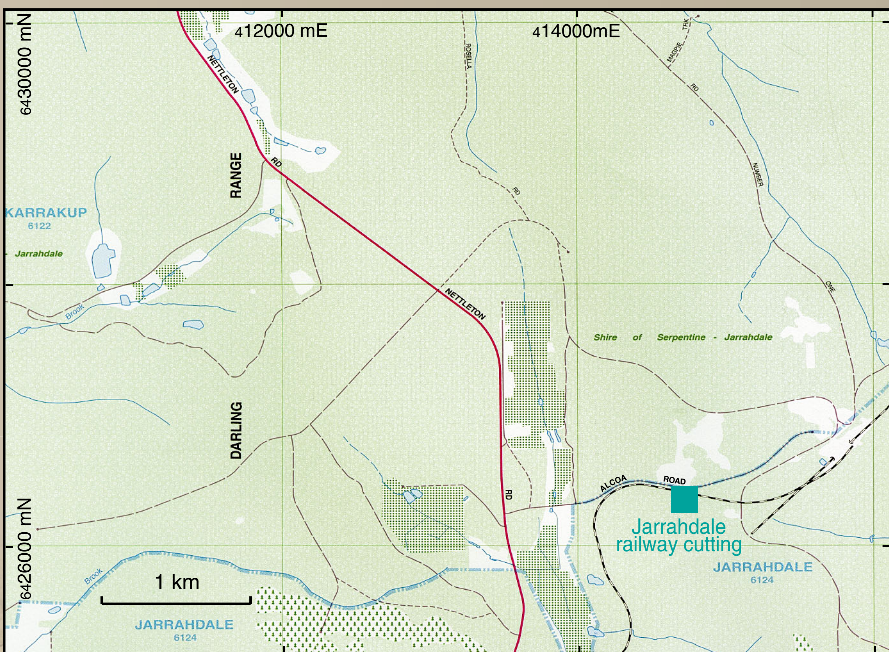


Figure 33. Location of the Jarrahdale railway cutting

The Darling Range east of the Darling Scarp has a widespread mantle of **lateritic material**. The lateritic material forms the remnants of what was once an extensive, low, undulating **peneplain**. The thick **lateritic profiles** overlying all rock types testify to a long period of intense weathering. This **lateritization** affects sedimentary units of known Eocene age (part of the Paleogene period), but not those of known Middle Miocene age (in the Neogene period); therefore, the major period of lateritic development was probably in the Oligocene (late Paleogene) and possibly lasted until the early Miocene (Johnstone et al., 1973). The generalized geological time scale on the inside front cover of this book shows all these periods. The thickest and most extensive lateritic profiles are between the Avon and Harris Rivers, and within 50 km east of the Darling Scarp (Hickman et al., 1992). The railway cutting at Jarrahdale, about 10 km east of the Darling Scarp, is the ideal site to observe the development of the thick lateritic profile over different rock types.

How do lateritic profiles form?

Lateritic profiles are the result of a combination of deep and intense weathering, erosion, and deposition, modified by later soil-forming (pedogenic) processes on near-surface rocks. In recent years, the origins of the lateritic profiles have again been debated (Davy and Gozzard, 1995; McFarlane, 1983; Milnes et al., 1985; Ollier and Galloway, 1990; Ollier, 1991), with two main scenarios put forward. The first is the result of intense weathering of bedrock producing a strongly cemented ferruginous hardcap (**duricrust**) by a relative accumulation of iron. This process is driven by groundwater movement or capillary action, whereby iron is leached from weathered bedrock by groundwater, and subsequent evaporation causes the iron to precipitate out of solution and form a cement to the weathered material. In this case there would be a direct genetic association between the duricrust and the underlying materials depleted in iron. In the second scenario, the ferruginous hardcaps form in, or on, the floors or lower slopes of ancient valleys by the absolute accumulation of iron. In this scenario, iron dissolved in groundwater moves laterally through the soil profile and precipitates out of solution on lower ground.

A typical lateritic profile in the Darling Range is distinctly zoned. A complete profile has, from the base upward: parent rock (fresh bedrock); saprock, which is the zone of slightly weathered rock; **saprolite**, which is composed mainly of white, sandy kaolinitic clays that retain some of the parent rock fabric; an earthy, mottled zone; cemented ferruginous duricrust, rich in gibbsite and hematite; and loose, superficial iron-rich nodules, fragments, and pisoliths. The zones commonly merge into one another. Some well-preserved lateritic profiles are covered by a residual sandy soil, though in many cases the sandy soil has been removed by erosion. A profile may be completely preserved, partly or completely truncated, covered by more recent soils or transported material, or a combination of these. The topography of the surface of the bedrock can be more irregular than that of the ground surface, especially where pinnacles of bedrock are present or where there are **core-stones** high in the profile.

The typical profile is commonly thought to have formed under intense or deep weathering in seasonally tropical climates where relatively high temperatures and rainfall (possibly with some dry periods) have persisted for a long time (see Bardossy and Aleva, 1990; McFarlane, 1983; Ollier, 1991). However, there is increasing evidence that lateritic profiles can form under wet, cool to cold climates given sufficient time (Taylor et al., 1992). Brimhall et al. (1991) also suggested that the profiles of the Darling Range contain a significant amount of wind-blown (eolian) material.

Regardless of the environment of formation, the degree to which weathering has proceeded is controlled by the nature of the material being weathered, the timing of weathering, the characteristics of the groundwater, and the topographical setting.

The weathering process

Weathering generally proceeds from the surface downwards. Initially, weathering of fresh parent rock only happens along the boundaries of the minerals, and along joints and fractures, and is usually evident as iron staining. This slightly weathered rock is called saprock. As weathering proceeds, more of the weatherable minerals in the rock are altered, usually to kaolinite, goethite, and hematite. Only quartz and other resistant minerals remain unaffected in this material, which is called saprolite. Even though the saprolite can be distinctly weathered, it is still possible to identify the original texture and structure of the parent rock. With further weathering the original texture and structure of the parent rock is completely lost and iron is redistributed within the profile to form large

segregations. These iron-rich segregations, called mottles, contrast markedly with the surrounding paler coloured matrix and give this material its name — mottled zone. Overlying the mottled zone may be a layer of cemented ferruginous duricrust, which is a dense, dark-brown to black, iron-rich material that characteristically has a nodular to pisolithic fabric. Duricrust is formed within the zone of watertable fluctuation in the upper parts of the weathered profile — iron that has been redistributed from elsewhere in the profile is precipitated as nodules and pisoliths under the oxidizing conditions found in this zone. Commonly, loose, superficial iron-rich nodules and pisoliths overlie the duricrust, formed when the underlying duricrust breaks down into fragments.

The influence of bedrock on the materials of the overlying weathered profile can be most pronounced and it is possible to distinguish the lithology of the bedrock from examination of the weathered material. Anand et al. (1989) and Hickman et al. (1992) provided full details of the composition and mineralogy of lateritic profiles in the Darling Range.

Complete exposed sections through lateritic profiles are relatively rare. The deep railway cutting at Jarrahdale (Fig. 33) is probably the only such exposure in the Perth Region. The railway cutting is 650 m long and up to 15 m deep. Sadleir and Gilkes (1976) described in detail the lateritic profile at this site and two annotated, large-format photographs depicting aspects of the geology of both the north and south sides of the cutting can be examined on site at the bedrock outcrop.

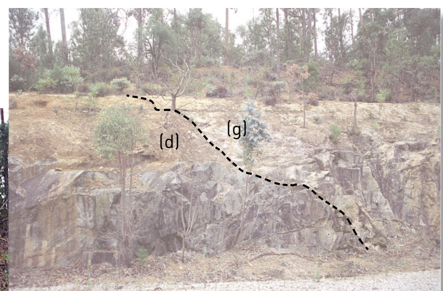
Bedrock in the railway cutting consists of Archean **gneissic** metagranites — which originally formed as **monzogranites** — intruded by northeasterly to northwesterly trending, metamorphosed quartz **dolerite** dykes. However, fresh bedrock is only visible over a distance of about 125 m, about half way along the cutting. The remaining sections of the cutting expose white and mottled kaolinitic saprolite clays, the weathering products of rocks with a **granitic** composition.

In the central part of the railway cutting, developed over the fresh bedrock, is a complete lateritic profile. From the base up, there are a number of distinct zones within the profile: fresh bedrock; pale-brown or red and white mottled clay; brown, earthy matrix containing lateritic nodules; ferruginous duricrust composed of brown to red, **pisolitic**, **nodular**, and **vermiform** material in an **indurated**, mainly quartz-rich matrix; and loose, nodular and pisolitic gravelly sandy soil at the surface.

Despite the intensely weathered nature of the materials in the exposed profiles, simple visual examination reveals the significant differences between the profile developed over metagranites and that developed over dolerites. It is clear that, even in the uppermost parts, the profile retains characteristics that can be related to the parent rock. Figure 34 shows the contact between the gneissic metagranite and the main intruding dolerite dyke. The sharp contact between these rock types is clearly seen at the base of the cutting, and the contrasts in colour and texture of the weathered material above the fresh bedrock allow the intrusive contact to be identified and followed up the weathered profile. Close inspection shows that, even in the ferruginous duricrust at the top of the profile, the contact is preserved.

A measured section 370 m east-southeast of the car park on Alcoa Road (MGA 414750E 6426380N) shows the lateritic profile over the dolerite intrusion. Above the basal 2.6 m of fresh metamorphosed quartz dolerite is about 12 cm of greenish grey, stained yellowish brown, loose, extremely weathered nodular material (Fig. 35). This is overlain by 2.3 m of red and white kaolinitic clay, mottled yellowish brown, and containing core-stones of dolerite. This is overlain by 2.7 m of tightly packed lateritic nodules in a brown to yellowish brown, earthy matrix. The nodules increase in size and abundance up the profile as this material grades into a 1.6-m layer of red to reddish brown, nodular and vermiform, ferruginous duricrust. Within the duricrust, there are highly weathered residual boulders with a core of fresh dolerite (Fig. 36). The duricrust is overlain by 0.5 m

Figure 34.
Contact between metagranite (g) and the main dolerite dyke (d) in the Jarrahdale railway cutting (MGA 414735E 6426400N) traceable through the lateritic profile



of superficial, loose, nodular and pisolitic lateritic gravel in a yellowish brown silty sand matrix.

A measured section of the lateritic profile over the gneissic metagranitic bedrock can be seen about 15 m to the northwest (MGA 414740E 6426390N). Here the basal 2.8 m of coarse-grained gneissic metagranite with occasional veins of **pegmatite** is overlain by 2.2 m of coarse, gritty, grey, kaolinitic clay, mottled pale brown to yellowish brown, containing abundant angular to subangular, medium- to coarse-grained quartz grains with some gravel-sized quartz crystals. The kaolinitic clay becomes more mottled farther up the profile. Overlying the grey kaolinitic clay is 1.7 m of pale-brown, coarse, gritty, kaolinitic clay, slightly mottled grey, containing abundant angular to subangular, medium- to coarse-grained quartz grains with some gravel-sized quartz crystals. This pale-brown clay is overlain by 0.4 m of tightly packed lateritic nodules in a yellowish brown sandy silt matrix. The nodules increase in size and abundance up the profile. This material grades up into a 0.9-m layer of brown to yellowish brown, nodular and pisolitic, quartz-rich, ferruginous duricrust, over which is 0.5 m of superficial, loose, nodular and pisolitic lateritic gravel in a yellowish brown silty sand matrix.

By comparing the sections above the metamorphosed dolerite and gneissic metagranite, it is clear that the lateritic profiles are influenced by the underlying geology. Quartz is dominant throughout the profile developed over the metagranite, even up to and including the ferruginous duricrust, whereas quartz is almost totally absent throughout the profile developed over the dolerite. Other mineralogical and geochemical patterns are also apparent (Sadleir and Gilkes, 1976) and have been used to confirm that the intensely weathered lateritic profiles exposed in the Jarrahdale railway cutting have developed in situ over contrasting rock types.

Getting there

Access to the Jarrahdale railway cutting is unrestricted. The cutting is no longer in operation and the railway tracks have been removed. Travel approximately 5 km along Nettleton Road from its junction with Jarrahdale Road north of the township of Jarrahdale. Turn east along Alcoa Road from its junction with Nettleton Road (MGA 413510E 6426240N) and park in the car park on the south side of Alcoa Road at the end of the bituminized section of the road (MGA 414390E 6426475N). The main section of the cutting is approximately 370 m east along the cutting from the car park.

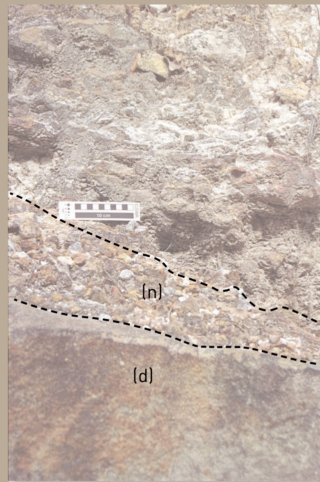
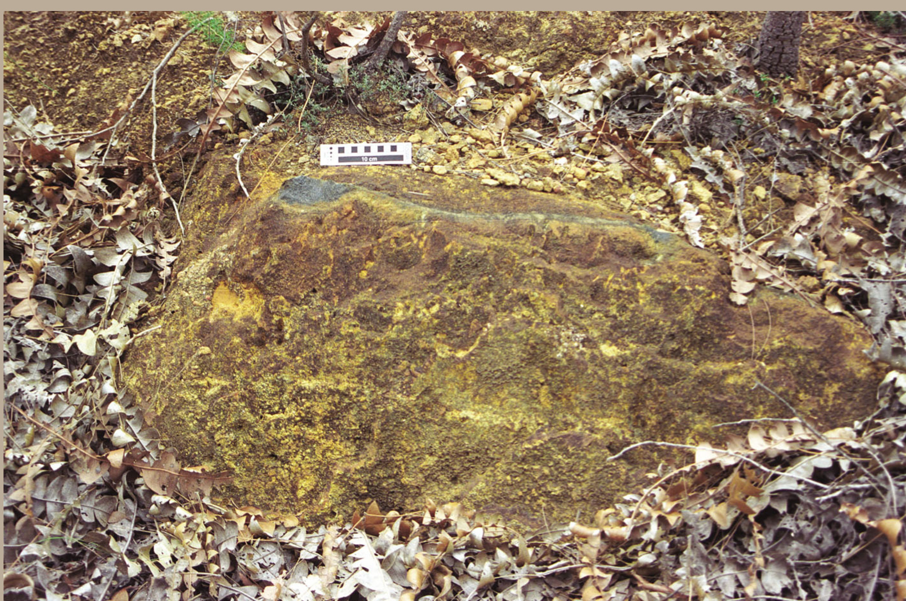
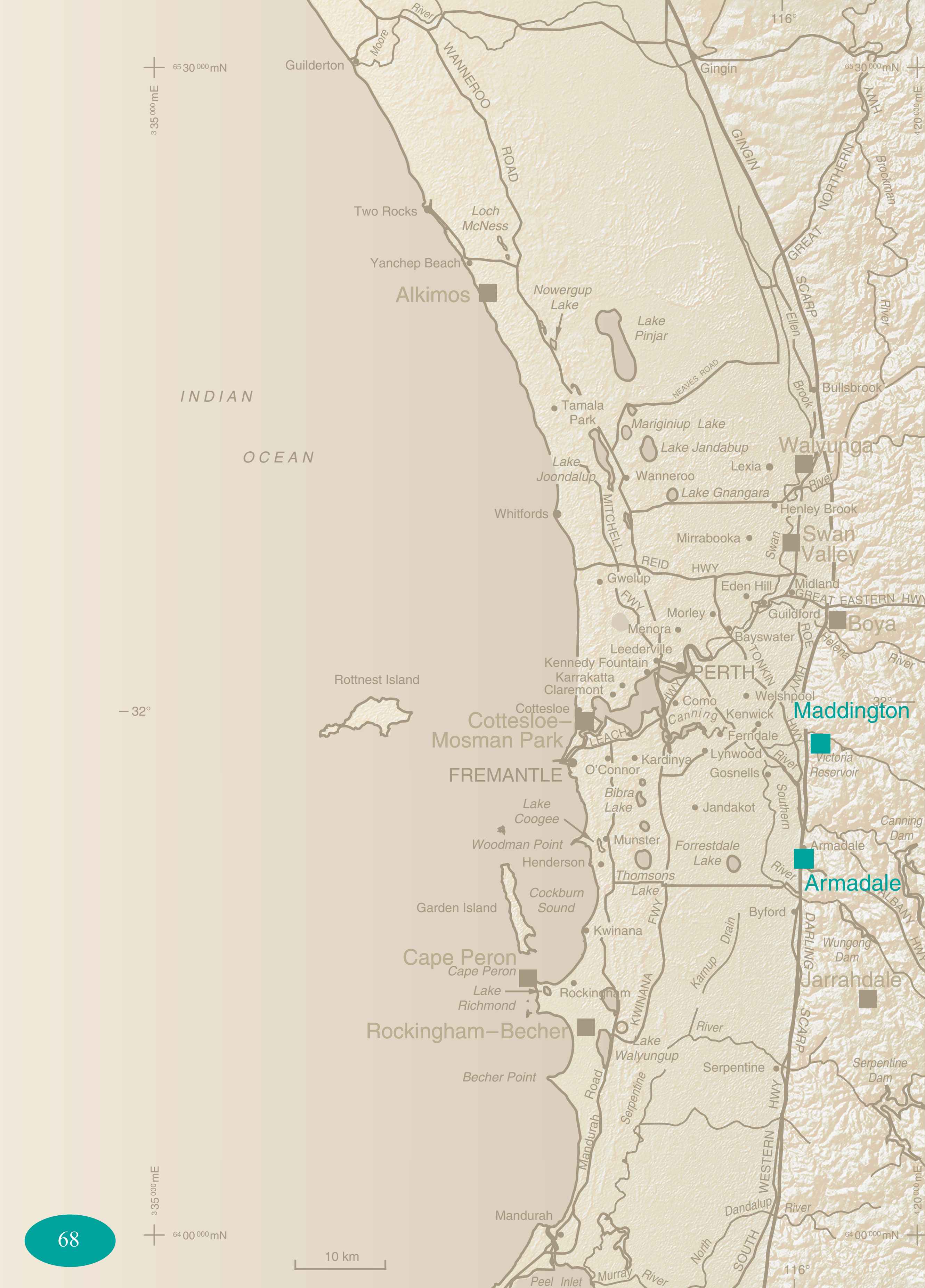


Figure 35.
Basal, extremely weathered nodular material (n) overlying fresh dolerite (d) in the Jarrahdale railway cutting (MGA 414750E 6426395N

Figure 36.
Residual boulder with a core of fresh dolerite in the Jarrahdale railway cutting (MGA 414750E 6426395N)





Guilderton
Moore
River
WANNEROO
ROAD
Gingin
116°
65 30 000 mN
3 35 000 mE
4 20 000 mE
GINGIN
HWY
GREAT
NORTHERN
Brockman
River
Two Rocks
Loch McNess
Yanchep Beach
Alkimos
Nowergup Lake
Lake Pinjar
SCARP
Ellen
Brook
Bullsbrook
NEAVES ROAD
INDIAN
OCEAN
Tamala Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lexia
Lake Joondalup
Wanneroo
Lake Gnangara
River
Henley Brook
Whitfords
MITCHELL
Mirrabooka
Swan
Swan Valley
REID
HWY
Gwelup
Eden Hill
Midland
FWY
GREAT EASTERN HWY
Morley
Guildford
Menora
Boya
Bayswater
ROE
Helena
River
Leederville
TONKIN
Kennedy Fountain
Karrakatta
PERTH
Claremont
Rottnest Island
32°
Como
Welshpool
Cottesloe
Canning
Kenwick
Maddington
Cottesloe–Mosman Park
LEACH
Ferndale
Lynwood
Victoria Reservoir
Kardinya
FREMANTLE
O'Connor
Gosnells
Bibra Lake
Southern
Lake Coogee
Jandakot
Canning Dam
Woodman Point
Munster
Forrestdale Lake
Armadale
Henderson
Thomsons Lake
Armadale
Cockburn Sound
Garden Island
Byford
ALBANY
Kwinana
Drain
DARLING
Wungong Dam
Cape Peron
Karnup
Jarrahdale
Rockingham
Lake Richmond
KWINANA
Rockingham–Becher
Lake Walyunga
Serpentine
Serpentine Dam
Becher Point
Road
Mandurah
WESTERN
Dandalup
North
SOUTH
64 00 000 mN
10 km
Peel Inlet
Murray
River

ARMADALE–MADDINGTON

Sporadic outcrops of metamorphosed shale, siltstone, and sandstone lie along the foot of the Darling Scarp, evidence that an ancient ocean once existed here

Maddington Quarry, now disused (see Figure 41)

At the foot of the Darling Scarp, weakly metamorphosed shale, siltstone, and sandstone, with minor amounts of **conglomerate**, outcrop in a narrow belt (up to 1 km wide) between Maddington and Serpentine. This sequence of rocks belongs to the Cardup Group (Low, 1972; Playford et al., 1976; Wilde and Low, 1980) and outcrops only sporadically along the foot of the Darling Scarp, between the Darling Fault to the west and Archean rocks of the Yilgarn Craton to the east (Fig. 2).

Although now metamorphosed, the Cardup Group rocks are clearly sedimentary in origin. The rocks strike parallel to their contact with the Archean rocks, and dip at moderate to steep angles (50–60°) to the west. Within the shales and siltstones there is a well-developed slaty **cleavage** subparallel to the bedding (Wilde and Low, 1980). Most outcrops of the Cardup Group are intruded by a suite of **dolerite** dykes.

A relationship debate

The relationship of the Cardup Group to the Archean rocks of the Yilgarn Craton and the nature of the contact between the two was originally the source of some debate. Foreman (1937) thought that the contact between the two was intrusive, with younger **granites** intruding the older sedimentary rocks. He also suggested that the **gneisses** immediately to the west of the outcrop of the Cardup Group were originally sedimentary rocks that were altered by a granitic **magma**. However, Prider (1941), on the basis of detailed mapping together with considerable petrographic work, was able to show that the granites are older than the Cardup Group, and thus inferred an **unconformity** between the two. Unfortunately, because of poor exposures, he was unable to determine the exact nature of the contact. It was not until the unconformity was exposed in a quarry at Maddington (see below) that the relationship inferred by Prider (1941) was ultimately confirmed.

The age of the Cardup Group sedimentary rocks is uncertain. Volcanic rocks in similar sedimentary rocks, found near Moora along the Darling Fault to the north, have an age of 1390 million years. It is thought that the age of the Cardup Group may be similar (Fitzsimons, 2003). The sedimentary rocks must be older than the dykes. Although attempts have been made to date them (Compston and Arriens, 1968), the results are not reliable.

The Cardup Group is subdivided into three formations (Low, 1972; Playford et al., 1976): the Whitby Sandstone, Neerigen Formation, and Armadale Shale.

The Whitby Sandstone (oldest formation) rests unconformably on Archean rocks, and is considered to be the basal unit of a marine sequence deposited during a gradual rise in sea level (**marine transgression**). It is a thin (up to 40 m), discontinuous unit comprising a basal pebble to boulder conglomerate that grades up into fine- to coarse-grained sandstone or quartzite.

The Neerigen Formation conformably overlies the Whitby Sandstone, or is unconformable on the Archean rocks where the Whitby Sandstone is absent. It consists of thin sandstones interbedded with **fissile**, ripple-marked shale. The thickest section known is that in a quarry at Cardup where it is 73.4 m thick. The Neerigen Formation is thought to be a marine unit, but this cannot be conclusively demonstrated.

The Armadale Shale (the youngest formation) conformably overlies the Neerigen Formation, and is a thick sequence (at least 483 m thick) of black and white shales with minor amounts of thin sandstone and quartzite in which graded bedding and ripple marks have been noted. The upper parts of the formation are not exposed because of a widespread cover of younger Quaternary deposits. The Armadale Shale is thought to be a marine unit that was deposited primarily in a deep basin, but the presence of ripple marks and **stromatolites** suggests that at least part of the unit was deposited in shallow water.

Armadale

A disused shale quarry on Marsh Road at Armadale (Figs 37 and 38) provides excellent exposures of the Neerigen Formation and Armadale Shale of the Cardup Group. Shale from this quarry was extracted for brick and clay-tile production between 1902 and the early 1930s, and since then this quarry has been used as a teaching site.

Although the Whitby Sandstone is not exposed in the quarry, it is present in outcrop and as loose material immediately to the east of the quarry. The contact between the Whitby Sandstone and underlying Archean rocks can be seen in Bedfordale Hill Road, 200 m southeast of the quarry, and in a roadside exposure in Carrack Road, 150 m northeast of the quarry. It was from exposures at this quarry and from the surrounding area that Prider (1941) correctly inferred the relationships between the Cardup Group and the Archean rocks, although at these locations the true relationship between the Cardup Group and the Archean rocks cannot be conclusively demonstrated.

The geology of the quarry is relatively simple. A unit of silty shales overlies a basal quartzite. These units are part of the Neerigen Formation. At the top of the Neerigen Formation is a thin **carbonate** bed about 80 cm thick. The conformably overlying Armadale Shale comprises a thick sequence of black shales overlain by white shales (Fig. 38).

The quartzite at the base of the Neerigen Formation is typically white to pale yellowish green in colour, although it weathers to a yellowish brown colour, and consists mainly of slightly rounded quartz grains several millimetres in diameter. The rock also contains occasional slightly rounded grains of a green mineral (epidote) as well as microcline. These minerals are typical of those found in the Archean granites immediately to the east of the Armadale Quarry. The presence of such minerals in the quartzite together with textures in the rock formed during its deposition, such as medium-scale cross-bedding and ripples, clearly indicate that the quartzite was deposited in shallow water from material derived from the erosion of the Archean granites immediately to the east, and that the place of deposition was very close to the granitic source rocks.

Overlying the quartzite is a sequence of silty shales. These shales are similar in colour to the quartzite, can be easily split along bedding planes (they are fissile), and contain some ripple marks produced by water currents. The formation of the shales indicates a deepening of the marine basin in which the Cardup Group was deposited.

The uppermost unit of the Neerigen Formation is the thin carbonate unit seen in the east of the quarry. Development of the carbonate unit implies that the sea in which it was deposited was shallow and relatively warm, similar to some tropical seas of today, and that there was little material being transported into the sea from the adjacent landmass.

The Armadale Shale overlies the Neerigen Formation without a break and is well exposed in the northern part of the quarry (Fig. 38), where it is seen to comprise a thick sequence of black shales overlain by white shales. Although the black shales are finely bedded, the alternation of both white and dark-grey to black coloured bands throughout the unit can be clearly seen. It is the darker bands that give the black shales their dominant colouration. The main minerals in the bands of both colours is the same, a white, fine-grained clay mineral called sericite, together with some extremely fine quartz. The colouration of the darker bands is caused by evenly spread, finely disseminated graphite-like material. The white shales are very similar in composition to the underlying black shales except that they do not contain any of this dark-coloured graphite-like material.

A dolerite sill intrudes the Armadale Shale in the western wall of the quarry, but unfortunately there is no complete section. The most easily examined blocks are on the quarry floor. Prider (1941) described contact metamorphism in the sedimentary rocks adjacent to the sill, where the heat of the intrusive sill caused minor alteration (hornfelsing) of the shale. The outer edges of the sill have a chilled margin, where the intrusive magma cooled and crystallized relatively quickly, producing a much finer grained texture than that of the interior. Prider (1941) also noted that the dolerite sill itself was intruded by a thin (0.3 m thick) **microporphyritic** metamorphosed dolerite sill.

Figure 37. Location of the Armadale Quarry

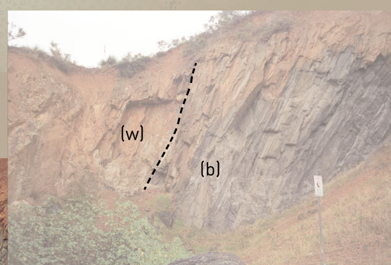


Figure 38.
General view of the steeply dipping black (b) and white (w) shales of the Armadale Shale in the Armadale Quarry (MGA 407565E 6441680N)

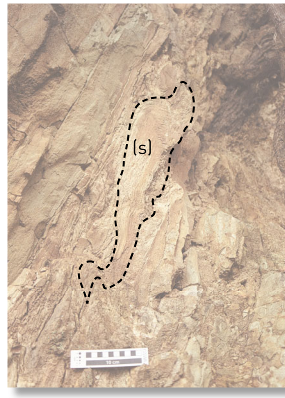


Figure 39.
Detail of the stromatolites (s) in the Armadale Quarry
(MGA 407565E 6441680N)

Fairbridge (1953) first recorded stromatolites from the Cardup Group at the Armadale Quarry, and located them in the lower part of the Armadale Shale. However, they appear to be confined to a single layer near the top of the Neerigen Formation, just below the carbonate layer that forms the uppermost unit of the Neerigen Formation (Fig. 39). Grey (1987) described the stromatolites as hemispherical, slightly flattened domes, characterized by wavy laminae and fenestrae, with wave crests superimposed across several laminae. The domes are 15–50 cm in diameter, and some are elongate, probably caused by the action of water currents. She concluded that the stromatolites cannot be taxonomically identified, and that the name *Collenia*, used by Fairbridge (1953), is incorrect.

Getting there

The Armadale shale quarry is on Marsh Road, Armadale. Parking is available on Marsh Road close to the quarry. Access to the quarry is restricted because of the unstable nature of the walls of the quarry. Permission to enter the site must be obtained from the City of Armadale.

Maddington

The only exposure in the Perth Region of the unconformity between the Cardup Group and the underlying Archean rocks can be seen in a disused shale quarry at Hayward Road in Maddington (Fig. 40). It was from exposures at this quarry that the true relationship between the Cardup Group and Archean rocks inferred by Prider (1941) was verified. The Orange Grove Brickworks extracted shale of the Neerigen Formation from this quarry for brick making until the 1970s.

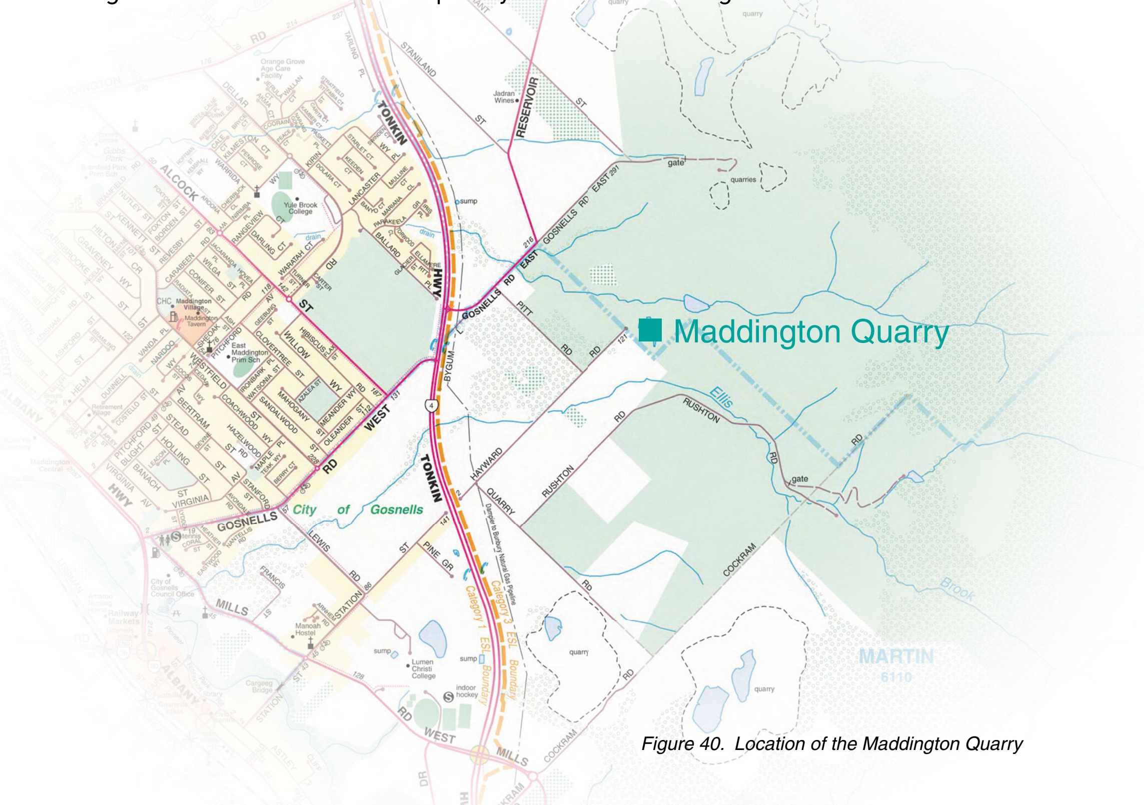


Figure 40. Location of the Maddington Quarry

The unconformity is visible along the upper bench on the east side of the quarry (Fig. 41). It is gently undulating, with amplitudes of between 10 and 20 cm, and the contact dips 60° towards the west. Here the Whitby Sandstone (the oldest formation of the Cardup Group), an 8 m-thick unit of pebble conglomerate and interbedded grit, rests directly on the underlying Archean granites (Fig. 42). At the base of the Whitby Sandstone is a pebble conglomerate less than 10 cm thick, consisting of rounded pebbles of quartz, averaging about 1 cm in diameter, set in a gritty matrix of quartz and feldspar and interstitial silt. This passes upwards into a sequence of alternating coarse-grained quartz sandstones and poorly sorted clayey sandstones. Within this unit, sedimentary structures such as ripple marks, tabular cross-bedding, and shrinkage cracks are evident. The uppermost 5 m of the Whitby Sandstone is made up of alternating thin beds of cleaner sandstones and siltstones.

The Whitby Sandstone is typical of a marine transgressive sequence. Pebble conglomerates are commonly found at major unconformities, where they are laid down by the action of waves moving across a bare landscape and eroding the underlying rocks. The rounded shape of the pebbles is indicative of transport by water over considerable distances. Ripples and cross-bedding in the finer grained sandstones are evidence of deposition in relatively shallow water by the action of waves.

The siltstones of the uppermost Whitby Sandstone pass upwards into pale, cream–grey shales of the Neerigen Formation. The Neerigen Formation contains several decimetre-scale beds of sandstone close to the boundary with the Whitby Sandstone, but these die out within a few metres of the contact. A moderate cleavage can be seen in the muddier sedimentary rocks.

The shales of the Neerigen Formation represent the continuation of the marine transgression as the sea gradually became much deeper. However, the occurrence of some beds of sandstone shows that the gradual deepening was punctuated by occasional retreats of the sea (regression), when shallower water intermittently prevailed.

The sedimentary rocks dip towards the southwest at an average angle of 60°, although the angles are variable throughout the quarry. Tilting of these sedimentary rocks is probably the result of movements on the Darling Fault, which is only some 1400 m west of the quarry.

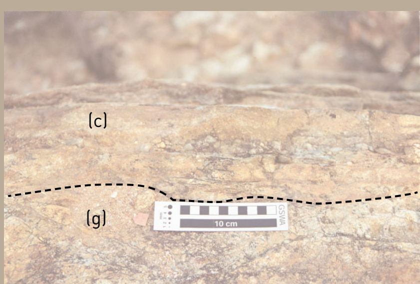
Defining the western limit of the quarry is a highly weathered, 40 m-wide, northerly trending dolerite dyke.

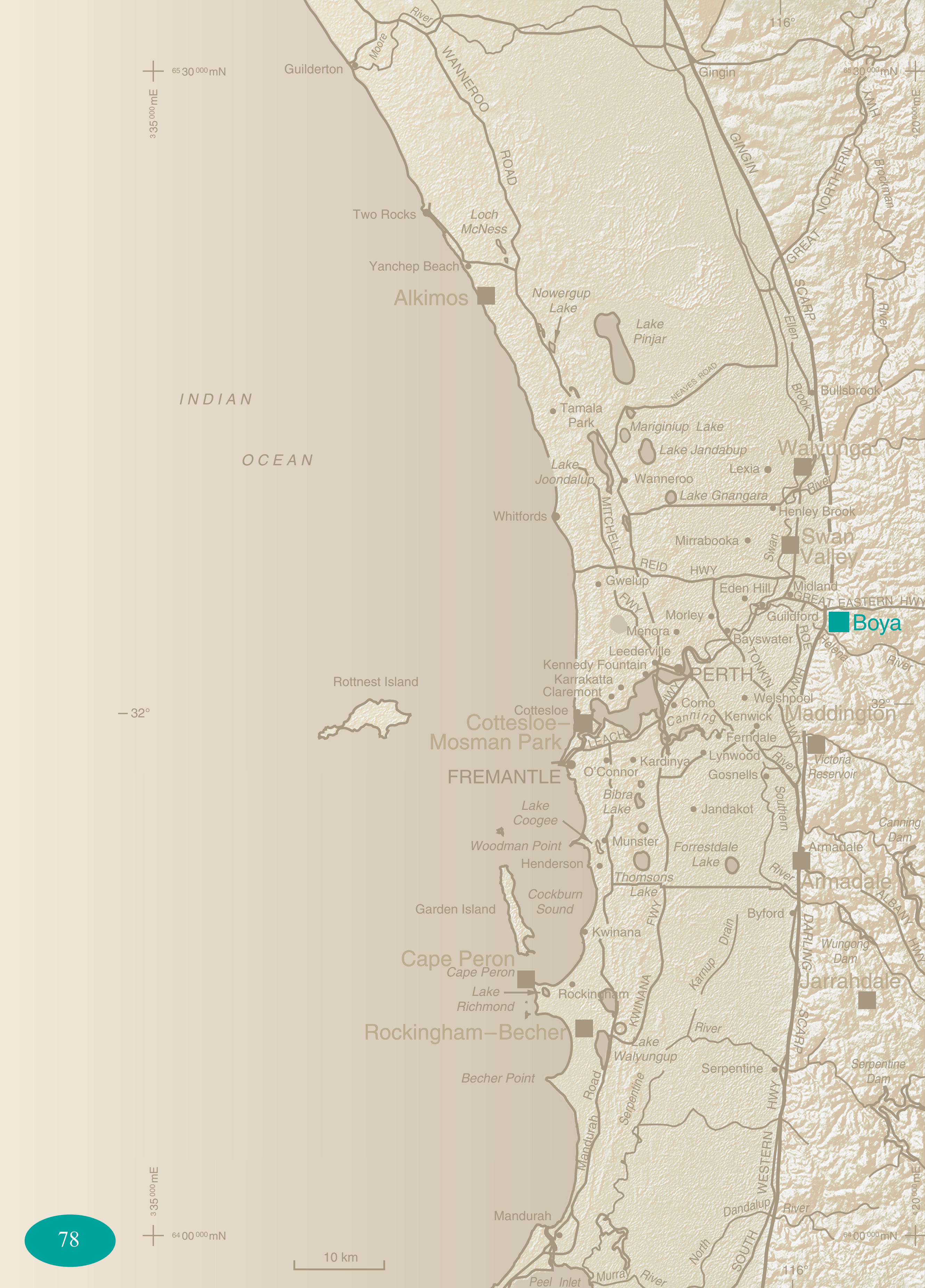
Getting there

The Maddington shale quarry is on private land at the northeast extent of Hayward Road, Maddington. Access to the quarry is restricted. Permission to enter the site must be obtained from the Department of Environment and Conservation.

Figure 41.
Maddington Quarry (MGA 408115E 6453180N). An unconformity is located on the upper bench in the left of the photograph at (u)

Figure 42.
Detail of the basal quartz-pebble conglomerate (c) of the Proterozoic Cardup Group unconformably overlying Archean granites (g) in the Maddington Quarry (MGA 408115E 6453180N)




Guilderton
Moore
River
WANNEROO
ROAD
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GINGIN
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NORTHERN
GREAT
HWY
Brockman
River
SCARP
Two Rocks
Loch
McNess
Yanchep Beach
Alkimos
Nowergup
Lake
Lake
Pinjar
Ellen
Brook
Bullsbrook
NEAVES ROAD
INDIAN
OCEAN
Tamala
Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lexia
Lake
Joondalup
Wanneroo
Lake Gnangara
Henley Brook
Whitfords
MITCHELL
Mirrabooka
Swan
Valley
REID
HWY
Gwelup
Eden Hill
Midland
GREAT EASTERN HWY
FWY
Morley
Guildford
Boya
Menora
Bayswater
ROE
Helena
River
Leederville
TONKIN
Kennedy Fountain
PERTH
Karrakatta
Claremont
Rottnest Island
Welshpool
32°
Como
Cottesloe
Canning
Kenwick
Maddington
Cottesloe–
Mosman Park
LEACH
Ferndale
Lynwood
Kardinya
O'Connor
Victoria
Reservoir
FREMANTLE
Gosnells
Bibra
Lake
Southern
Lake
Coogee
Jandakot
Canning
Dam
Woodman Point
Munster
Forrestdale
Lake
Armadale
Henderson
Thomsons
Lake
Armadale
Cockburn
Sound
ALBANY
Garden Island
Byford
Kwinana
Drain
DARLING
Wungong
Dam
Cape Peron
Cape Peron
Jarrahdale
Karnup
Lake
Richmond
Rockingham
KWINANA
Rockingham–Becher
Lake
Walyungup
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Serpentine
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64 00 000 mN
10 km
North
SOUTH
Peel Inlet
Murray
River

BOYA

The quarries around Boya provide excellent exposures close to Perth of the granites and cross-cutting dolerite dykes in the Archean Yilgarn Craton

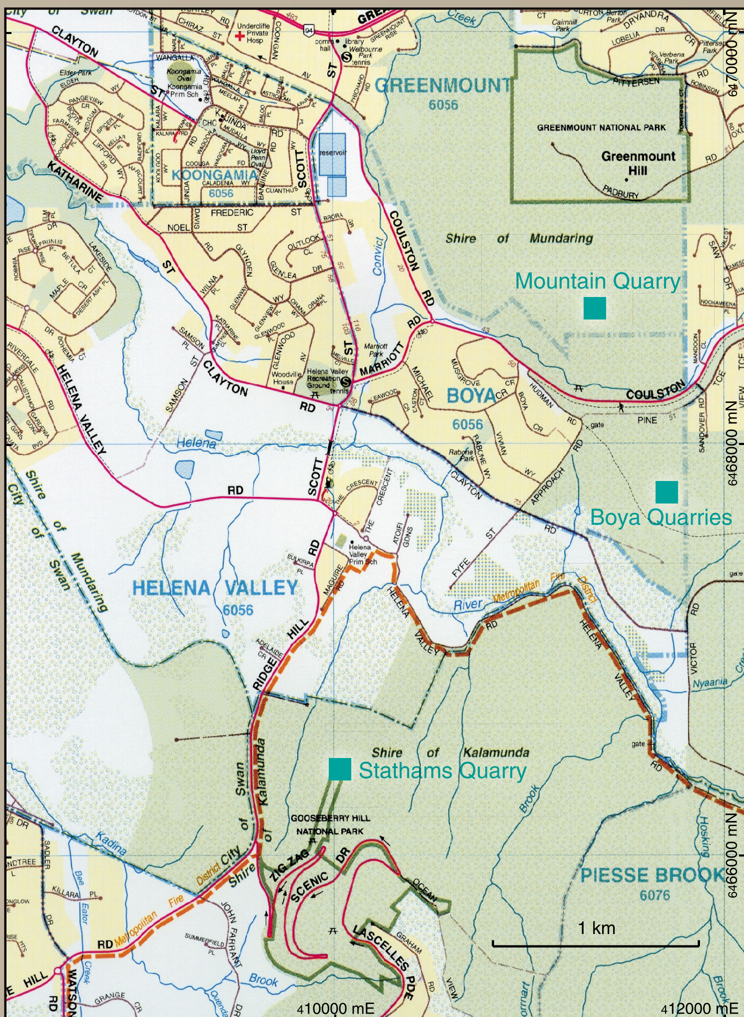


Figure 43. Location of the Darling Range quarries

The area east of the Darling Fault forms the hinterland of the Perth Region. This area is part of the vast Yilgarn Craton — an ancient region of varied rock types that occupies much of the southwestern part of Western Australia, stretching from Perth in the west to beyond Kalgoorlie in the east, and from Peak Hill in the north to the south coast of Western Australia. The Yilgarn Craton includes most of the gold-bearing **greenstone belts** of Western Australia.

In the Perth Region the main rock types of the Yilgarn Craton (Fig. 2) include **granite** and metamorphic rock (Wilde and Low, 1978; Wilde, 2001). The oldest rocks in the Perth Region are metamorphic rocks, and these outcrop in two well-defined belts in the northeast of the Perth Region — the Chittering Metamorphic Belt and Jimperding Metamorphic Belt. A third metamorphic belt, the Balingup Metamorphic Belt, and a belt of volcanic rocks near Boddington called the Saddleback Group, lie outside the boundaries of the Perth Region.

Marginal to the metamorphic belts are intimate associations of earlier **gneissic** material pervaded by a later **granitic** component, particularly around the metamorphic rocks of the Chittering Valley (Wilde, 2001).

Metamorphic belts near Perth

The Chittering Metamorphic Belt extends northwards along the Chittering Valley from near Bullsbrook for about 100 km in a narrow (10 km wide) belt adjacent to the Darling Fault. The main rock types are **gneisses** interlayered with schists. They were deposited as muds and sands in a shallow sea between 3170 and 2830 million years ago and were later deformed and metamorphosed into the rocks we see today (Nieuwland and Compston, 1981; Wilde, 2001).

The Jimperding Metamorphic Belt extends for over 200 km southwest from near New Norcia (100 km north-northeast of Midland) to beyond York (75 km east of Midland) and Beverley (90 km east-southeast of Midland). The rocks of the Jimperding Metamorphic Belt contrast markedly with those of the Chittering Metamorphic Belt, containing more quartzites and banded iron-formations. The rocks have also had a slightly different metamorphic history from those of the Chittering Metamorphic Belt (Nieuwland and Compston, 1981).

Between 2700 and 2600 million years ago, the metamorphic rocks and other rocks of the Yilgarn Craton were intruded by large volumes of granitic **magma**. This event led to the geological stabilization of the Yilgarn Craton. It is these granites that form most of the ancient **crystalline rocks** along the Darling Scarp. A variety of rock types can be seen, but monzogranites are most common, and there are a number of discrete bodies of **porphyritic** granite that have been extensively deformed and recrystallized, especially along the eastern margins of the Chittering Metamorphic Belt.

Swarms of **dolerite** dykes intrude the granites. They appear to be most abundant along the Darling Scarp close to the Darling Fault. These dykes were probably intruded as a result of the increasing fracturing of the crust during development of the Darling Fault in the Mesoproterozoic and Neoproterozoic.

Several quarries in close proximity to Perth offer exceptional exposures of the granites and dolerites of the Darling Range. Three of these quarries — Mountain, Boya, and Stathams — are close together in the Helena Valley east of Perth (Fig. 43). Clarke and Williams (1926) published the first geological map of this part of the Darling Range.

Mountain Quarry

Mountain Quarry (Fig. 43) was one of the first quarries to be developed in the Darling Range to supply hard-rock aggregate to Perth, mainly for road making. Here granites typical of the Darling Range are intruded by a number of dolerite dykes (Fig. 44).

At first sight, the granites appear to be even textured. However, closer examination reveals that there are three distinct textural phases. The earliest phase is a fine-grained, greyish **granodiorite** consisting of the minerals plagioclase, quartz, and microcline, with interstitial biotite. This rock type is cut by a coarser grained granite that ranges from granodiorite to monzogranite in composition. This later phase is finer grained near the contact with the earlier phase, and encloses **xenoliths** of the earlier, finer grained granodiorite (Fig. 45).

The last phase of granite intrusion includes the subhorizontal veins of **pegmatite**, which are seen throughout the quarry cutting across both of the earlier granites (Fig. 45).

Proterozoic, dark-coloured dolerite dykes cut across all the granites, and the contacts between them are very well exposed. At these contacts, the dolerite displays a finer grained texture characteristic of chilled margins, where the magma was rapidly cooled during or immediately after intrusion.

How old are these rocks?

The dating of the granites of Mountain Quarry is problematic. Libby and de Laeter (1978) used rubidium–strontium (Rb–Sr) methods to date the biotite minerals from these rocks and obtained ages of 548 to 452 million years. However, whole-rock analyses of the same rocks, using the same method, returned ages of between 2560 and 2160 million years. Nemchin and Pidgeon (1997) obtained an age of between 2690 and 2626 million years using the uranium–lead (U–Pb) dating method on zircon grains, which is more consistent with the known ages of granites from elsewhere in the Yilgarn Craton. Resetting of the Rb–Sr isotopes in the granites of the Darling Range was probably the result of long-lived movements along the Darling Fault throughout the Proterozoic and into Paleozoic times.

A dyke in the Darling Scarp near Perth and another dyke 100 km inland, near York, gave U–Pb zircon ages of around 1215 million years. Most dykes along the western Yilgarn Craton margin are thought to be this age and are related to the Marnda Moorn large igneous province (Wingate and Pidgeon, 2005).

Although both the granites and the dolerites exposed in the quarry show well-developed jointing, it is expressed more clearly in the granites (Fig. 44). The joints in the rocks are parting surfaces that have formed as a result of the reduction in volume of the rock as it cooled and consolidated from magma. Later crustal movements, particularly movement along the Darling Fault, may have further accentuated the development of these joints. Many of the dolerite dykes have been intruded along fractures in the granites.

In general, larger igneous bodies will show the most prominent joints because, although these bodies will have taken much longer to solidify, they will have undergone a correspondingly larger reduction in volume as they solidify. In contrast, smaller igneous bodies, such as dolerite dykes, cool more quickly, undergo a relatively small reduction in volume on solidifying, and consequently show fewer joints.

Deep and intense **lateritic weathering** of the granites is evident in the southwest corner of the quarry. Here, a thin, truncated **lateritic profile** can be examined. **Core-stones** of granites are also present in higher levels of the weathered zone. One of the differences in the way in which dolerites weather when compared with granites is illustrated by the development of erosional hollows over the dolerites (Fig. 44). These are noticeable in the southeast of the quarry.

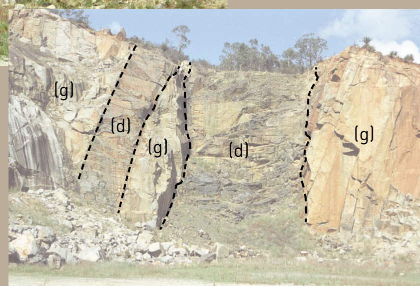
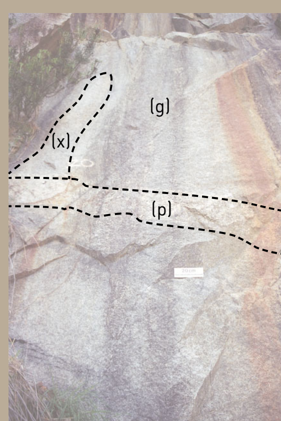


Figure 44.
Dolerite dykes (d) intruding well-jointed granites in Mountain Quarry (MGA 411320E 6468615N). Notice the prominent erosional hollow over the wide dolerite dyke (d)

Figure 45.
Xenolith of finer grained granodiorite (x) in coarser grained granite (g), and a late-stage subhorizontal pegmatite vein (p) in Mountain Quarry (MGA 411320E 6468615N)



The Jarrahdale section of this guide reviews the significant differences in the way that weathering affects granites and dolerites. Of the factors affecting weathering, the mineralogy of the material being weathered is of major importance. Granites are generally medium- to coarse-grained rocks mainly composed of minerals, such as quartz, which are highly resistant to weathering. Consequently these rocks tend to weather slowly.

In contrast, dolerites contain ferromagnesian minerals (minerals rich in iron and magnesium) which, in the Darling Scarp area, weather easily and quickly to form finely divided clay minerals or become dissolved in the groundwater. These clay minerals and the dissolved portions are readily removed from the weathering profile.

Getting there

Access to Mountain Quarry is unrestricted. However, permission to enter the quarry should be obtained from Landgate (formerly Department of Land Information). Parking is available at the picnic site immediately north of Coulston Road at Boya (MGA 411095E 6468320N). From the picnic site, follow the track 350 m northeast to the quarry.

Boya Quarries

The Boya Quarries are located approximately 900 m south-southeast of Mountain Quarry (Fig. 43). Three individual quarries are located in the area — Quarry No. 1 in the northwest, Quarry No. 2 in the centre, and Quarry No. 3 in the southeast (Fig. 46). In the quarries, two large dolerite dykes intrude granites of the Darling Range. Granite and dolerite were extracted from the Boya Quarries to supply hard-rock aggregate to Perth. Since their closure, these quarries have been used as teaching sites for many years.

As with the granites at Mountain Quarry, the granites at the Boya Quarries are, for the most part, medium to coarse grained and even grained in texture, and include the same phases of granitic intrusion, with an earlier phase of fine-grained, greyish granodiorite cut by a later coarser grained granite. As at Mountain Quarry the granites intruded about 2700 to 2600 million years ago.

Between Quarry No. 2 and Quarry No. 3, near the southeast entrance to Quarry No. 2, a small shear zone in the granite is exposed (Fig. 47). The shear zone trends nearly northerly (352°) and dips at 72° to the east-northeast. Here, the granites are deformed and have sheared along closely spaced, parallel shear

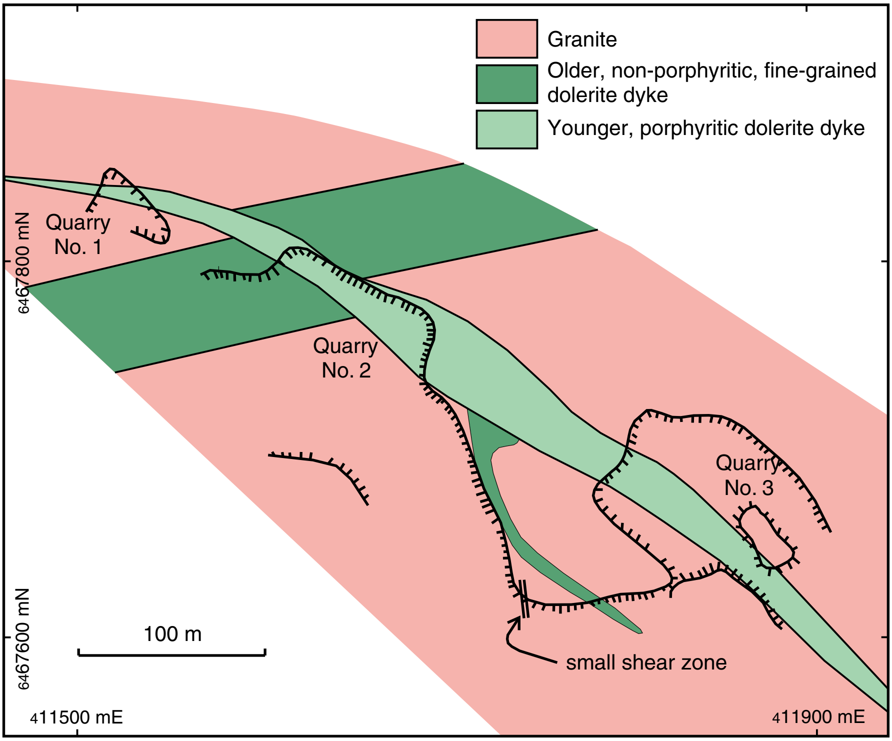


Figure 46.
Geological sketch map of the Boya Quarries (after field surveys by students at the University of Western Australia)

bands as a result of the sliding motion that occurred when adjacent parts of the rock were forced to move relative to each other because of movement along the nearby Darling Fault.

Of particular interest in the Boya Quarries is the presence of two dolerite dykes that show different relative ages, orientations, and compositions (Fig. 46). An older, larger dolerite dyke trending roughly east-northeast through Quarry No. 2 is cut and offset by a younger, northwesterly trending dolerite dyke. The younger dyke is porphyritic in texture (Fig. 48), and contains prominent white feldspars, but where it is in contact with the older dyke and granites it has a chilled margin devoid of **phenocrysts**. This younger porphyritic dyke is exposed in all three quarries, and varies in width from 17 m in Quarry No. 3 to about 20 m in Quarry No. 2, before thinning to 3–5 m in Quarry No. 1. **Xenoliths** of the granites can be seen in this younger porphyritic dyke close to the intrusive margin (Fig. 49), especially in Quarry No. 3.

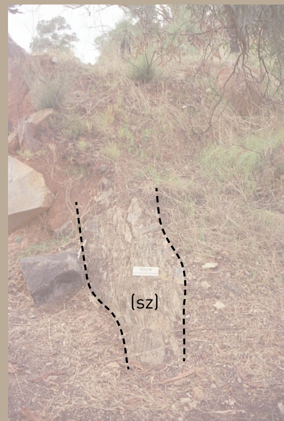


Figure 47.
Small shear zone (sz) in granite at the Boya Quarries (MGA 411755E 6467620N)

Figure 48.
Detail of the porphyritic dolerite dyke with white feldspar crystals at the Boya Quarries (MGA 411865E 6467695N)

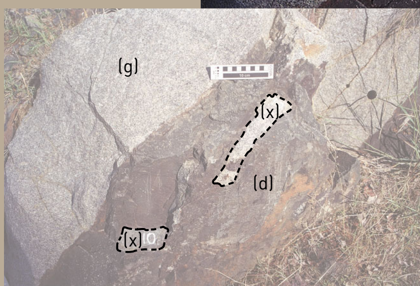
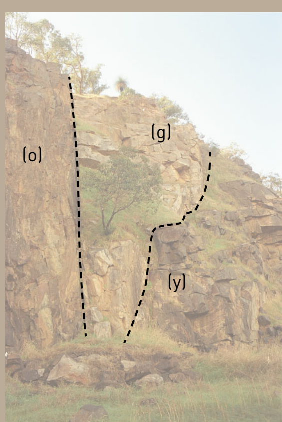


Figure 49.
Dolerite dyke (d) enclosing xenoliths of granite (x) at Boya Quarry No. 3 (MGA 411865E 6467695N). The margins of the xenoliths are very distinct

Figure 50.
View of Boya Quarry No. 2 showing the relationships between the older (o) and younger (y) dolerite dykes and the granites (g) they intrude (MGA 411670E 6467725N)



Getting there

Access to the Boya Quarries is unrestricted; however, permission to enter the quarries should be obtained from the Shire of Mundaring. Car parking is available immediately east of the electricity substation at the entrance to a gated track on the north side of Victor Road at Darlington. Follow the track north for 240 m before taking a second track that rises up the hill to the northwest. This track leads directly to the three quarries.

Stathams Quarry

Stathams Quarry (Fig. 43) is located approximately 2 km southwest of the Mountain and Boya Quarries. The area was originally mapped by Clarke and Williams (1926), and more-detailed mapping was carried out by Prider (1948).

The quarry exposes granite and two intruding dolerite dykes (Figs 51 and 52). The larger of the dolerite dykes provided the rock that was quarried for hard-rock aggregate in the early 20th century. The three distinct phases of granite intrusion (2700 to 2600 million years old) seen in the Mountain and Boya Quarries can also be seen in Stathams Quarry. The earliest phase was originally a coarse-grained, sometimes porphyritic granite that now exhibits a weak gneissic foliation (Fig. 53). This gneissic metagranite is intimately intermixed with a later phase of finer grained granite. The relative timing of these two phases can be seen in the southern face of the quarry, where xenoliths of the gneissic metagranite have been entrapped in the later, finer grained granite. The third phase includes the veins of pegmatite that can be seen throughout the quarry.

Deep and intense lateritic weathering of the granites is evident in the south-western corner of the quarry. Here, at the top of the quarry face, core-stones of granite can be seen in a clayey **saprolite** matrix.

Two altered dolerite dykes are exposed in the quarry. The larger dyke strikes approximately north-northwest and dips at 70° to the east. The narrower dyke strikes approximately north-northeast and also dips at 70° to the east. From the geological map in Figure 51 it can be seen that the two dykes are part of a complex network of dykes and are actually the same age.

Both dolerite dykes have essentially the same mineralogy and texture (Prider, 1948). The rocks are greenish black in colour, generally medium grained, but do show a tendency to finer grain sizes towards the margins of the intrusions. Late-stage hydrothermal alteration has resulted in a change to the original

mineralogy of the dolerite — dark-coloured pyroxene is replaced by a green, fibrous amphibole mineral, and pale-coloured plagioclase is replaced by yellowish green epidote, which also forms discrete pods and veins.

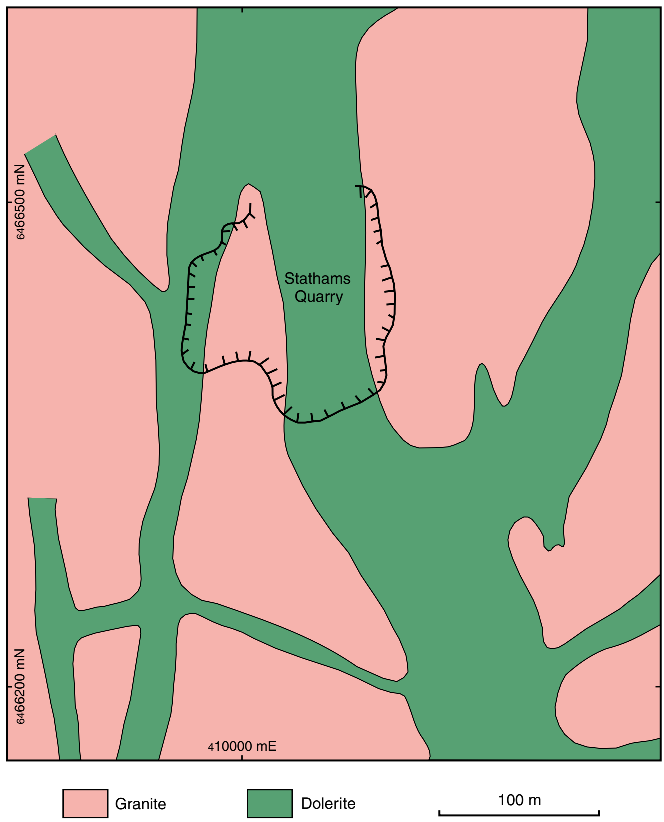


Figure 51.
Geological sketch map of Stathams Quarry

Getting there

Access to Stathams Quarry is unrestricted. Take Lascelles Parade from Gooseberry Hill and continue down Zig Zag Scenic Drive towards Ridge Hill Road. At the third major hairpin bend on Zig Zag Scenic Drive (MGA 409925E 6466080N) parking is available on open ground. From the car park take the gated track north-northeast towards the quarry. Some 300 m from the car park and 50 m north of the fence and gate that crosses the track, take the flight of steps on the left down to the quarry floor.

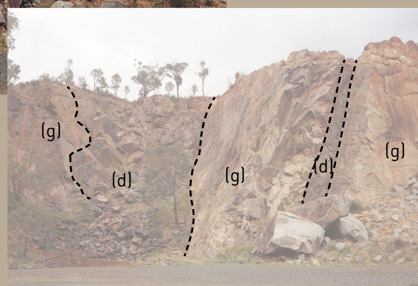
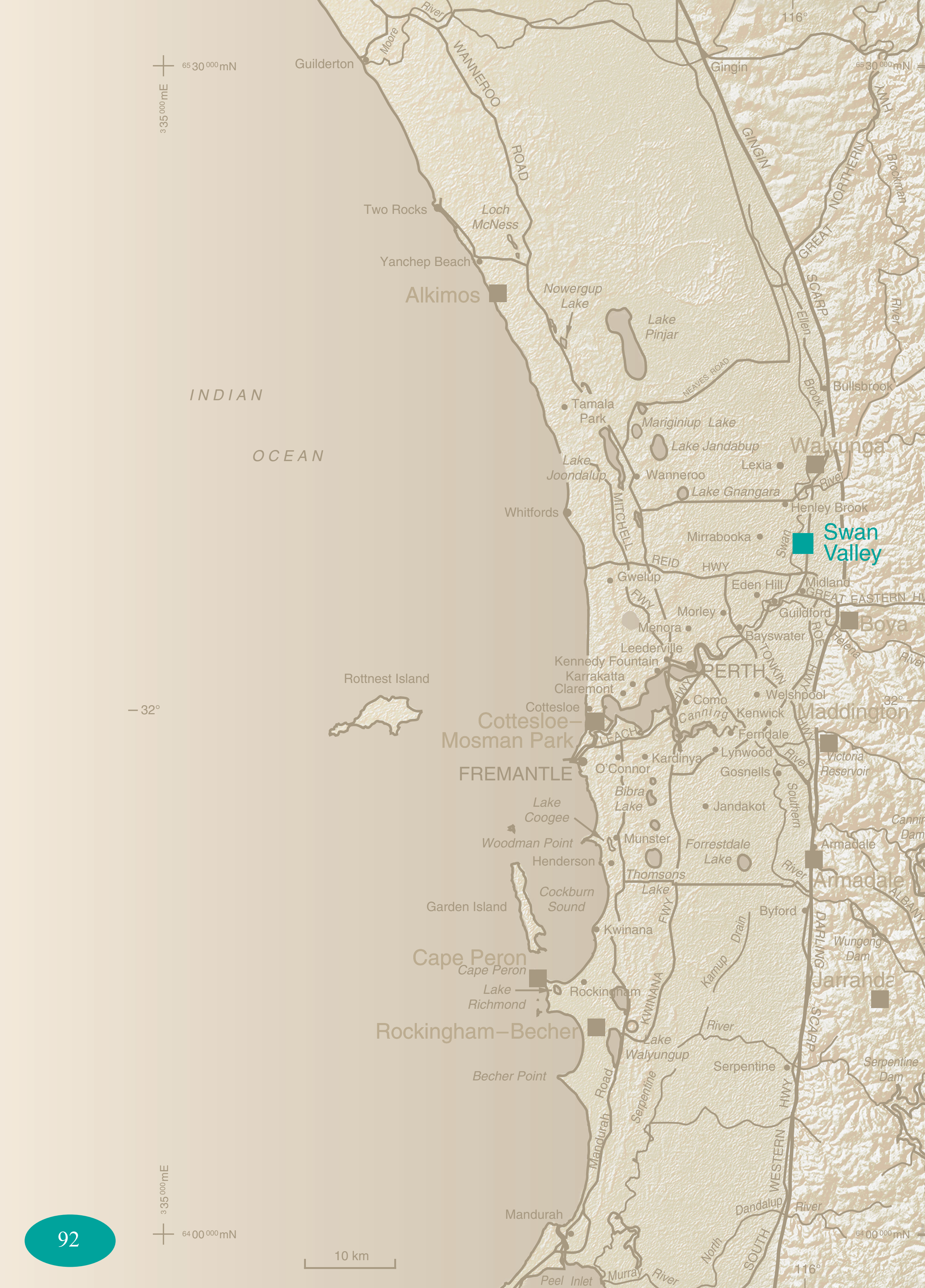


Figure 52.
View of the granites (g) and intruding dolerite dykes (d) at Stathams Quarry (MGA 410045E 6466465N)

Figure 53.
Detail of the coarse-grained porphyritic gneissic granite at Stathams Quarry (MGA 410045E 6466465N)



65 30 000 mN
3 35 000 mE
116°
Guilderton
Moore
River
WANNEROO
ROAD
Gingin
GINGIN
GREAT
NORTHERN
HWY
Brockman
River
Two Rocks
Loch
McNess
Yanchep Beach
Alkimos
Nowergup
Lake
Lake
Pinjar
SCARP
Ellen
Brook
NEAVES ROAD
Bullsbrook
INDIAN
OCEAN
Tamala
Park
Mariginiup Lake
Lake Jandabup
Walyunga
Lexia
Lake
Joondalup
Wanneroo
Lake Gnangara
River
Henley Brook
Whitfords
MITCHELL
Mirrabooka
Swan
Swan
Valley
REID
HWY
Gwelup
FWY
Eden Hill
Midland
GREAT EASTERN HWY
Morley
Guildford
Boya
Menora
Bayswater
ROE
Helena
River
Leederville
TONKIN
Kennedy Fountain
PERTH
Karrakatta
Claremont
HWY
Rottnest Island
Como
Welshpool
32°
Cottesloe
Canning
Kenwick
Maddington
Cottesloe–
Mosman Park
LEACH
HWY
Ferndale
Kardinya
Lynwood
River
Victoria
Reservoir
FREMANTLE
O'Connor
Gosnells
Bibra
Lake
Southern
Jandakot
Lake
Coogee
Canning
Dam
Woodman Point
Munster
Forrestdale
Lake
Armadale
Henderson
Thomsons
Lake
River
Armadale
ALBANY
Cockburn
Sound
Garden Island
FWY
Byford
Drain
DARLING
Wungong
Dam
Kwinana
Cape Peron
Cape Peron
Kamup
Jarrahdale
KWINANA
Lake
Richmond
Rockingham
SCARP
Rockingham–Becher
River
Lake
Walyungup
Serpentine
Serpentine
Dam
Becher Point
Road
Serpentine
HWY
Mandurah
WESTERN
Dandalup
River
Mandurah
64 00 000 mN
North
SOUTH
10 km
Peel Inlet
Murray
River

SWAN VALLEY

The history of the valley of the Swan River is shown in its river terraces, fluvial deposits, and floodplains

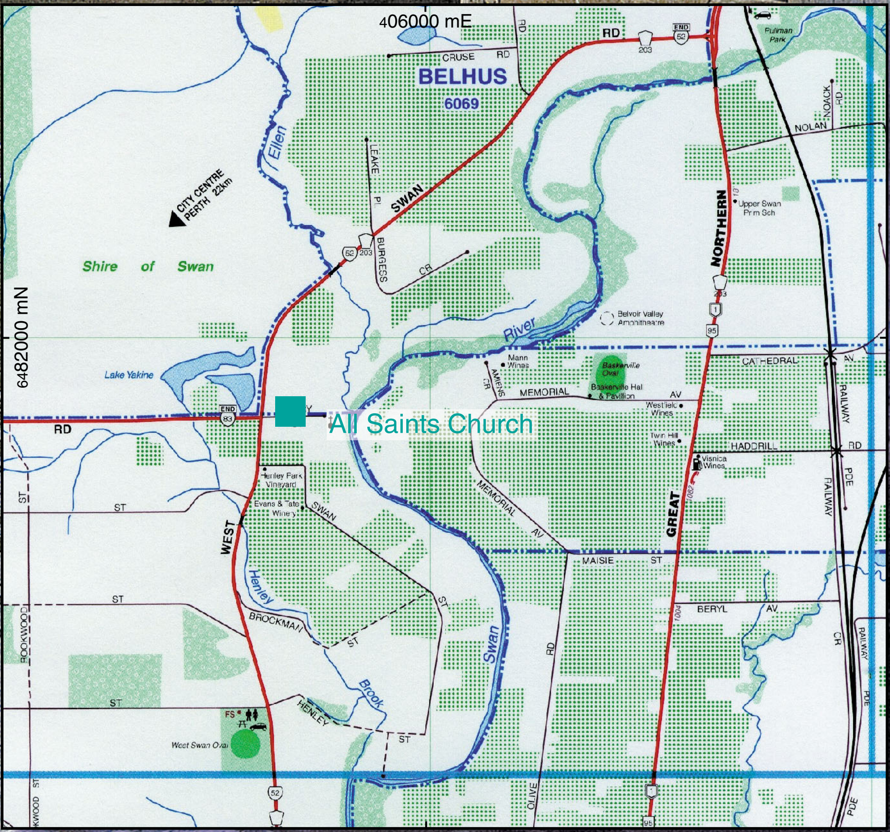


Figure 54. Location of All Saints Church, Henley Brook

Between the dune systems to the west and the **piedmont zone** of the Darling Scarp to the east lies the landform known as the Pinjarra Plain (McArthur and Bettenay, 1960) — an **alluvial** belt, 1.5 to 5 km wide, of mainly **unconsolidated** clays and loams deposited as **alluvial fans** near the **scarp** and floodplains along the rivers. In the Perth Region the two broadest areas of the Pinjarra Plain are the Swan Valley and Serpentine River flats. The development of the Pinjarra Plain between Guildford and Millendon is recorded in exposed sections along the Swan Valley, and highlights the influence of sea-level variations on landforms some distance from the shoreline.

The Pinjarra Plain (Fig. 5) coincides with and is underlain by the predominantly **fluvial** deposits of the Guildford Formation (Low, 1971). Aurousseau and Budge (1921) originally defined the Guildford Formation as the 'Guildford Clays', with the type area in the Swan Valley around Guildford. The formation consists predominantly of grey and brown clays and silts that were deposited as coalescing alluvial fans at the foot of the Darling Scarp (Gozzard, in prep.). These fans interfinger to the west in subcrop with sandy fluvial and estuarine sediments of the Gnangara Sand and Bassendean Sand. The unit varies in thickness, but is rarely greater than 25 m and commonly contains lenses of fine- to coarse-grained, poorly sorted sands and **conglomerates**, particularly in the Swan Valley.

Fairbridge (1953) identified a marine deposit within the Guildford Formation. This marine deposit is about 5 m above present sea level and contains the bivalve shells *Anadara* and *Dosinia* (Fairbridge, 1953). It is exposed in clay pits adjacent to the Caversham factory of Bristile Roofing, 2 km north of Guildford, and in clay pits at Folly Flats, 11 km east of Rockingham. However, based on geomorphological criteria at both localities, it is unlikely that the deposits in which the marine layer is found are part of the Guildford Formation sensu stricto and that they belong to the Perth Formation (Gozzard, in prep.).

The dramatic fall in sea level during the second-last glacial period brought deposition of the Guildford Formation to an end. A likely age range of Early Pleistocene to second-last interglacial period for the Guildford Formation seems valid.

In the Perth Region a number of rivers traverse the Pinjarra Plain and continue across the three north-trending dune systems. The largest of these is the Swan River, which flows in a southwest direction from the Darling scarp near Upper Swan to the Indian Ocean at Fremantle. The broad meanders of the Swan River are well illustrated in the cover photograph for this book. The Swan River is estuarine for most of its length; the limit of tidal influence lies just south of its confluence with Ellen Brook in Upper Swan.

The valley of the Swan River can be conveniently divided into three segments. The lower Swan River, which extends from Fremantle to Heirisson Island near

the centre of Perth, exhibits all the features of a drowned river valley or **ria**. The middle Swan River, between Heirisson Island and Guildford, flows in a wide, meandering valley, the sides of which are concealed by dunes of the Spearwood and Bassendean Dune Systems. The upper Swan River, from Guildford to the foothills of the Darling Scarp, flows in a valley that appears to have reached maturity following several successive rejuvenations. These rejuvenations are indicated by the development of a succession of **erosion terraces** between Upper Swan and Guildford. Jutson (1912) called this part of the Swan River valley 'precociously mature'.

All Saints Church

Below All Saints Church, on Henry Street in Henley Brook (Fig. 54), there is a prominent exposure of the Guildford Formation along the western bank of the Swan River. The exposed beds are about 80 m in length and 12 m in height, and reveal aspects of the **fluviatile** phase of the Guildford Formation.

The exposed section, from its base at river level, comprises a basal 3.3 m-thick bed of cross-stratified conglomerate with interbedded pods and lenses of cross-stratified sandstone (Fig. 55). The conglomerate is clast-supported and comprises fine- to coarse-grained gravel with some small cobbles predominantly of subangular to rounded vein quartz, black and brown lateritic nodules, and

Figure 55.
Cross-stratified conglomerate and sandstone of the Guildford Formation below All Saints Church (MGA 405770E 6481750N). Pebbles are visible in the conglomerate

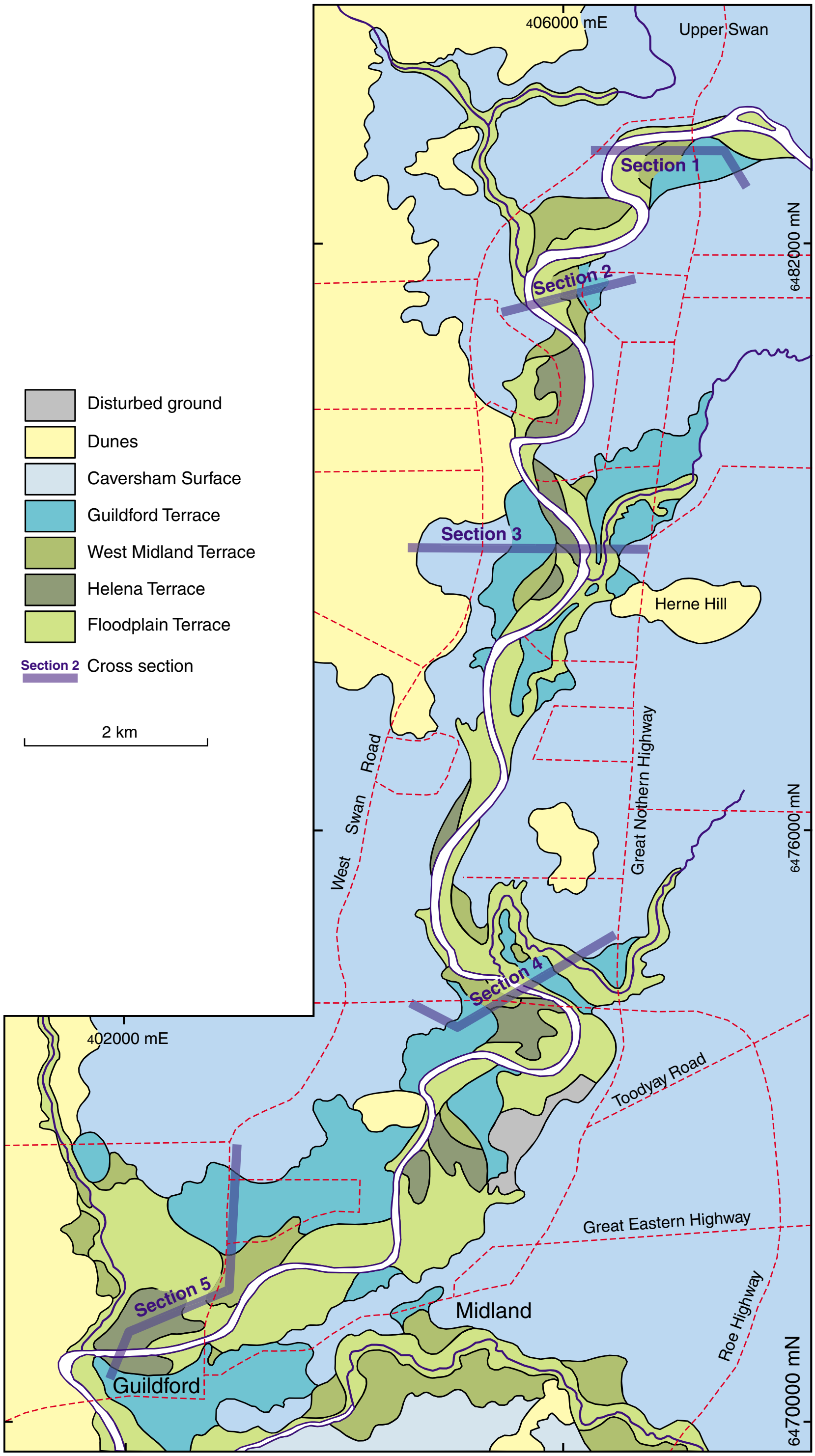


Figure 56.
Terraces of the Swan River between Upper Swan and Guildford. See adjacent figure for cross sections

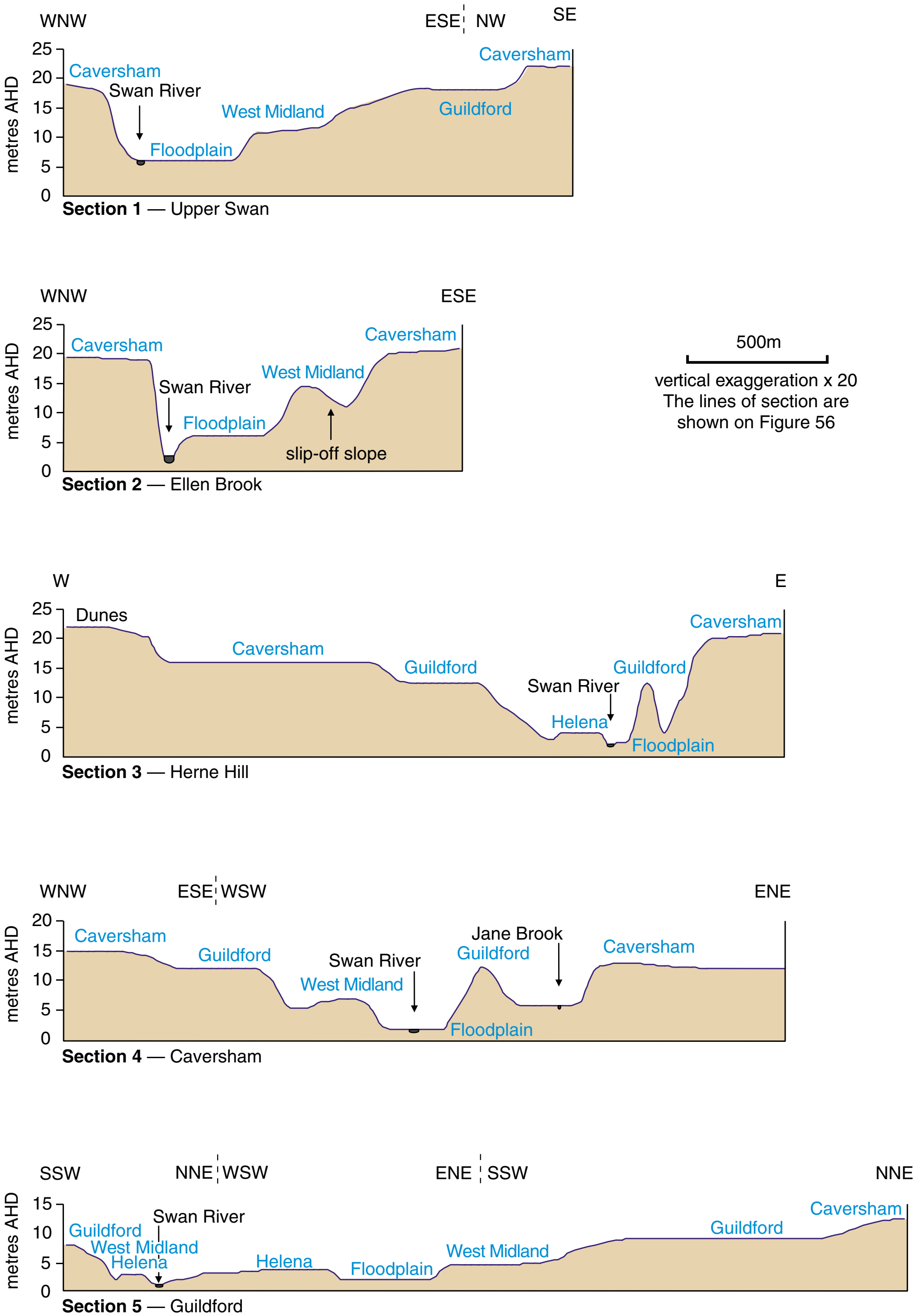


Figure 57.
Cross sections showing the terraces of the Swan River. Terrace names are shown in blue

some granite and **dolerite** in a coarse-grained sand and silty-sand matrix. The pebbles in the conglomerate are clearly derived from the Archean rocks of the nearby Darling Range.

The pods of sandstone are thin (mainly less than 30–40 cm thick), rarely laterally extensive, and comprise yellowish brown, medium- to coarse-grained subangular sand and silty sand. The cross-stratification in both the conglomerate and sandstones indicates deposition in a river system.

Overlying the basal conglomerate is a structureless, greyish brown, medium- to coarse-grained, subangular sandstone, up to 2.6 m thick, with frequent layers and bands of pebbles and grit. The pebbles are fine- to medium-grained gravel, predominantly of subangular to rounded vein quartz, with only a few pebbles of the other rock types seen in the basal conglomerate.

This greyish brown sandstone grades upward into a thick clay over a relatively short distance. The clay is more than 6 m thick and extends to the top of the section. It is grey, mottled yellowish brown, massive, structureless, and contains a few thin pebbly and gritty layers similar to those in the underlying sandstone.

This whole succession is a fining-upwards sequence of fluvial sediments that indicates a gradual reduction in river flow and a consequent diminution in the supply of coarser material.

Getting there

Access to the Swan River and the exposure at All Saints Church is unrestricted. Parking is available in the church car park at the eastern end of Henry Street, Henley Brook. From the car park a footpath leads eastward along the north boundary of the churchyard and then directly down to the river and the exposure.

Swan Valley

There are a number of broad river terraces, at several levels above the present river level, in the Swan Valley between Guildford and Upper Swan (Fig. 56). These terraces were formed by the erosion of former river floodplains related to successive falls in **base level**, which in the Perth Region is sea level. These falls rejuvenate the streams and rivers causing them to cut into their valleys and extend them upstream from their original source, leading to erosion along the valley. Ultimately, the remnants of the previous floodplains are exposed in the sides of the valley. These can be correlated downstream and used to construct a history of the development of the valley.

There are four terraces and one surface along the Swan Valley (Fig. 56). They were originally described by Aurousseau and Budge (1921), and show that there have been four cycles of erosion, each one caused by a lowering of base level. Figure 57 shows a series of cross sections at various locations along the Swan River. Figure 58 is a plot of the longitudinal profiles of the surface and terraces, and shows that the surface (Caversham Surface) and upper terrace (Guildford Terrace) have a significantly steeper profile than the lower three terraces. Together, Figures 56 to 58 show the areal extent of the terraces and the spatial and topographic relationships between the terraces and the surface.

The Caversham Surface (Fig. 56) is the highest feature in the Swan Valley. It coincides with the present surface of the Guildford Formation and represents the original erosion surface of the area. It changes in elevation from 21.3 m AHD at Upper Swan Bridge to 12 m at Guildford — in a distance of about 15 km.

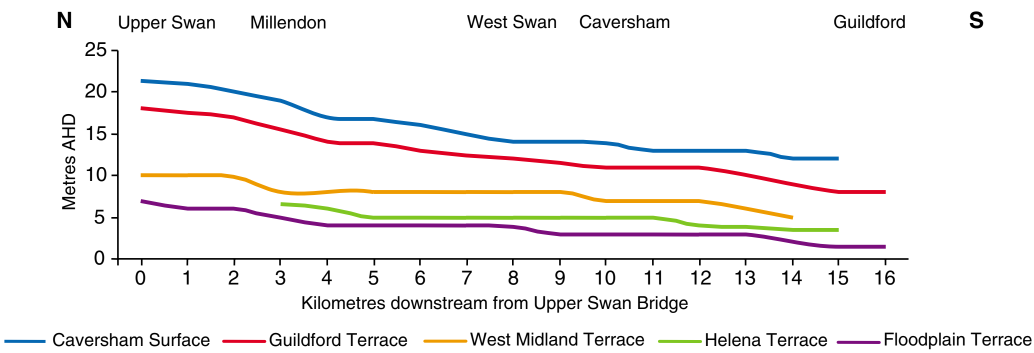


Figure 58. Longitudinal profiles of the Swan River terraces

The initial phase of erosion and rejuvenation cut into the Caversham Surface, resulting in the development of a relatively narrow, incised floodplain. This floodplain is consistently 3 m below the level of the Caversham Surface, resulting in a longitudinal profile (**thalweg**) that is parallel to it (Fig. 58). Remnants of this floodplain, which are termed the Guildford Terrace, are well developed throughout the length of the Swan Valley and can be seen at several sites, including Douglas Road in Henley Brook, between Caversham Avenue and Hamersley Road in Caversham, and along Lennard Street, off Barrett Street, in Herne Hill. The relative position of the Guildford Terrace, below the Caversham Surface and above the Floodplain Terrace, is very clear at Douglas Road (Fig. 59)

The erosional terrace produced by the second phase of down-cutting, which cut into, and below, the Guildford Terrace, is termed the West Midland Terrace (Fig. 56). Although it is recognizable along the whole length of the Swan Valley, it has been modified in places by subsequent fluvial processes. The West Midland Terrace has an elevation of 10 m (AHD) at Upper Swan Bridge, dropping to 5 m just east of Guildford.

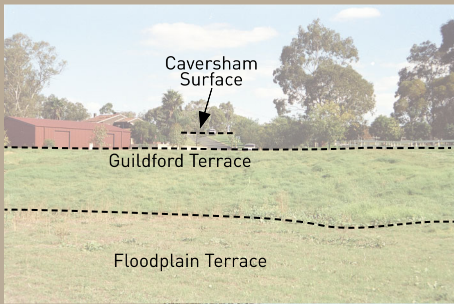


Figure 59.
View of the Caversham Surface (background), Guildford Terrace (middle ground), and Floodplain Terrace (foreground) at Douglas Road, Henley Brook (MGA 405800E 6478320N)

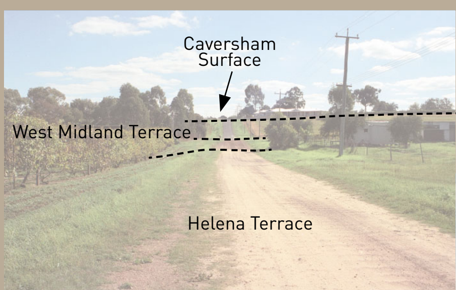


Figure 60.
View of the Caversham Surface (background), West Midland Terrace (middle ground), and Helena Terrace (foreground) on Swan Street, Henley Brook (MGA 406105E 6481010N)

The thalweg of the West Midland Terrace is much shallower than that of the Guildford Terrace (Fig. 58) — the height difference between the Guildford and West Midland Terraces increases upstream, from 4 m near Guildford to 8 m at Upper Swan. This suggests that there was significantly more time for down-cutting to approach base level in the upper reaches of the Swan River during development of the West Midland Terrace, or that the river had a greater erosional power under the influence of the rejuvenation.

The West Midland Terrace can be seen clearly on Swan Street in Henley Brook (Fig. 60), Hamersley Road in Caversham, and Padbury Avenue in Herne Hill.

The third phase of rejuvenation is not well preserved in the Swan Valley, but can be seen more distinctly in the valley of the Helena River south of Midland (Aurousseau and Budge, 1921). However, remnants of the Helena Terrace can be identified in the Swan Valley on both banks of the Swan River at Guildford. Here, a low terrace can be seen about 1.5 m below the level of the West Midland Terrace (at 3.5 m AHD). This same height difference between the Helena Terrace and the West Midland Terrace is seen at Millendon, but between Millendon and Guildford, the height difference between these two terraces is as much as 3 m (Fig. 58). The Helena Terrace can also be seen on Swan Street in Henley Brook (Fig. 60), south of Middle Swan Road in Caversham, and at Padbury Avenue in Herne Hill.

Figure 61.
View of the slip-off slope (a long, low, gentle slope) at Memorial Avenue, Baskerville (MGA 406445E 6481450N)

The lowest terrace along the Swan Valley is the Floodplain Terrace (Figs 56 and 58). It is the contemporary floodplain of the Swan River and is at a height of 7 m AHD at Upper Swan Bridge, descending to 1.5 m AHD at Guildford. It is consistently about 1 to 1.5 m below the level of the Helena Terrace.

In a meandering river, the force of the water cuts into and erodes the steep, outer, downstream bank (or cutbank). The eroded material is forced downwards toward the bottom of the channel by the turbulent water, then across and back up to the surface to be deposited on the inner bank. As the meandering river migrates through this ongoing process of erosion from one bank and deposition on the other, a long, low, relatively gentle slope known as a slip-off slope forms on the inner bank of the meander. This feature can be seen at Memorial Avenue in Baskerville (Fig. 61), and immediately south of the Upper Swan Bridge, west of the Great Northern Highway. At Upper Swan Bridge, the slip-off slope developed on the Guildford Terrace during the phase of rejuvenation that resulted in the development of the West Midland Terrace. At Memorial Avenue, the slip-off slope developed on the West Midland Terrace during down-cutting to the level of the Helena Terrace (Fig. 57, section 2).

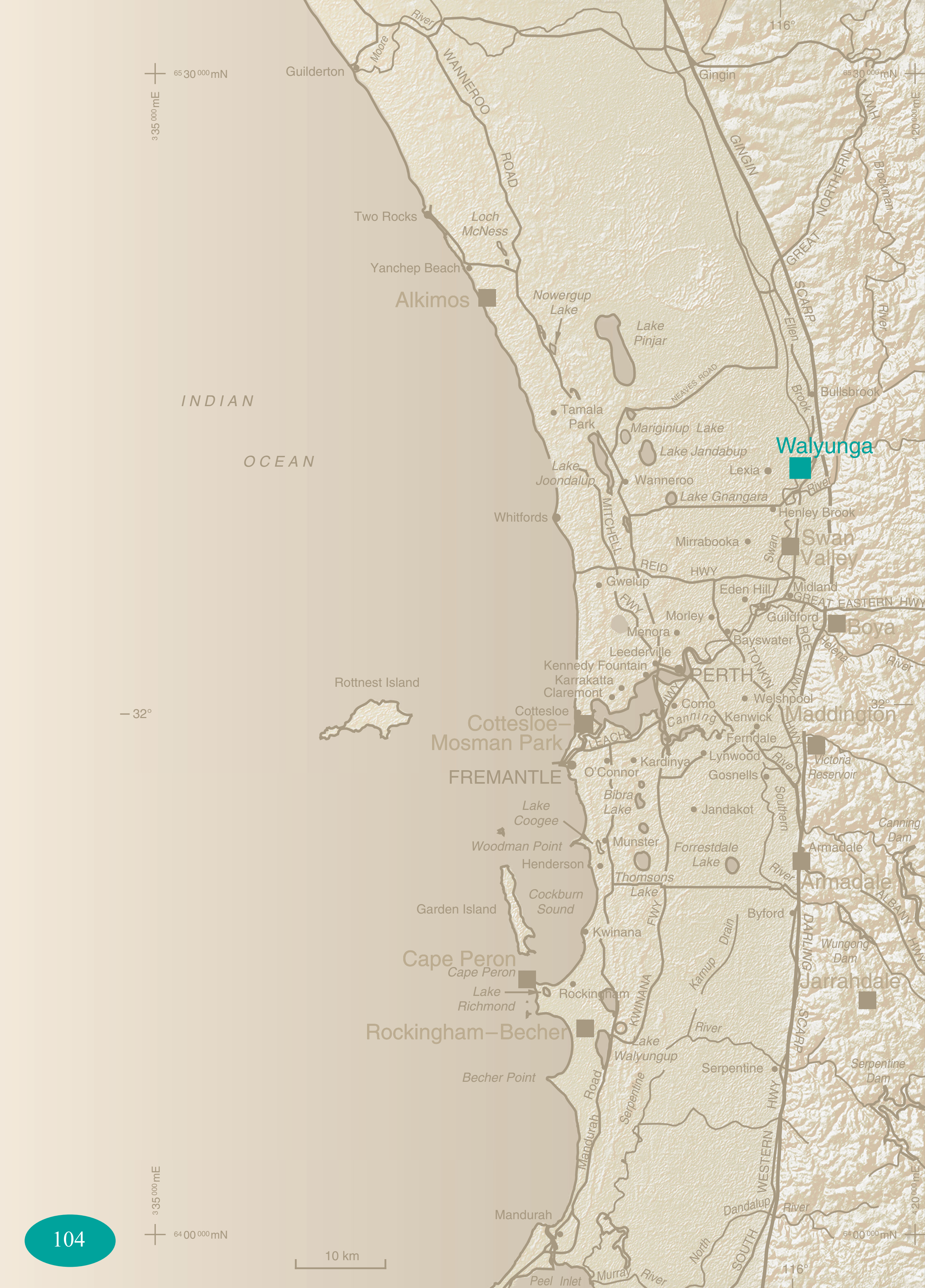
Getting there

Numerous major and minor public roads provide unrestricted access throughout the Swan Valley. All sites in the Swan Valley mentioned in this guide can be accessed without the need to enter private property. If you wish to enter private property you must first obtain the agreement of the landowner.

More evidence for sea-level changes — this time in the Swan Valley

Aurousseau and Budge (1921) showed that the total lowering of base level (sea level) between the second and fourth rejuvenations was about 6.7 m. This value is remarkably close to the 7 m that Somerville (1920) deduced for 'uplift' of the lower Swan Valley based on a study of marine shell beds, wave-cut platforms, and raised spits. From this evidence, Aurousseau and Budge (1921) concluded that the lowering of base level recorded by the terraces of the Swan Valley represents an actual measure of the change in base level. This means that Guildford, which is currently about 8 m above sea level, must have been close to sea level.

Aurousseau and Budge (1921) went on to attempt a correlation between the terraces of the Swan Valley and the marine shell beds exposed in the Cottesloe – Mosman Park area based on the height data given by Somerville (1920). They concluded that the West Midland Terrace could be correlated with the shell beds at Minim Cove, Peppermint Grove, and The Coombe. However, this correlation can no longer be substantiated in full because of the recognized age differences between the shell beds at Peppermint Grove and The Coombe (both last interglacial) and those at Minim Cove (second-last interglacial). Aurousseau and Budge (1921) also suggested that the Helena Terrace could be equated with the shell beds at Hinemoa Rock (Mosman Park) and Mudurup Rocks (Cottesloe), and that the Floodplain Terrace could be correlated with the shell beds at the Vlamingh Memorial and on the foreshore at Cottesloe immediately south of the Beach Street groyne. Although such correlations between the Swan Valley terraces and marine shell beds farther downstream are inviting, further work is needed to substantiate them.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Moore River
WANNEROO ROAD
Gingin
GINGIN
116°
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4 20 000 mE
Two Rocks
Loch McNess
Yanchep Beach
Alkimos
Nowergup Lake
Lake Pinjar
NEAVES ROAD
GREAT NORTHERN HWY
Brockman River
SCARP
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Bullsbrook
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Lake Jandabup
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Wanneroo
Lake Gnangara
Henley Brook
Whitfords
MITCHELL FWY
Mirrabooka
Swan Valley
REID HWY
Gwelup
Eden Hill
Midland
GREAT EASTERN HWY
Morley
Guildford
Menora
Boya
Bayswater
Leederville
Helena River
Kennedy Fountain
PERTH
TONKIN HWY
ROE HWY
Rottnest Island
Karrakatta
Claremont
Welshpool
32°
Cottesloe
Como
Canning
Kenwick
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Henderson
Thomsons Lake
Cockburn Sound
Garden Island
Byford
ALBANY HWY
DARLING SCARP
Kwinana
Drain
Wungong Dam
Cape Peron
Rockingham
Karnup
Jarrahdale
Lake Richmond
KWINANA FWY
Rockingham–Becher
River
Lake Walyungup
Becher Point
Serpentine
Serpentine Dam
Road
HWY
Mandurah Road
WESTERN
Dandalup River
Mandurah
64 00 000 mN
10 km
North
SOUTH
Peel Inlet
Murray River

WALYUNGA

The geology and landforms at Walyunga offer a window into the whole geological history around the Perth Region, from the ancient Archean rocks to present-day sediments

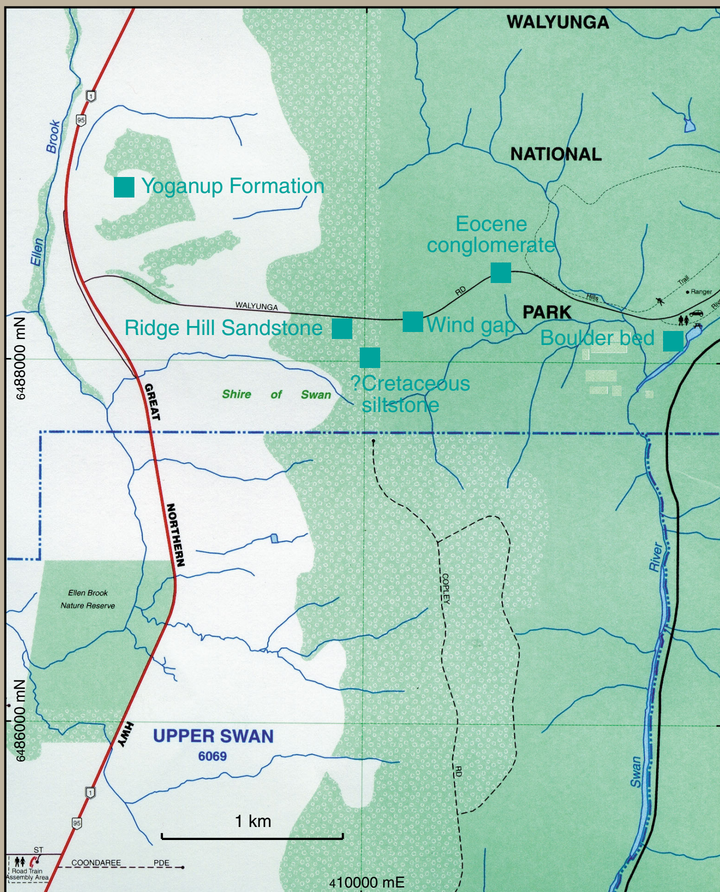

Figure 62. Walyunga locations

The Walyunga National Park and its surrounds straddle the Darling Scarp and its foothills. There are outcrops of Archean rocks, sediments of possible Cretaceous age, as well as Pleistocene and younger rocks.

The Ridge Hill Shelf is a complex geomorphological feature that forms part of the foothills of the Darling Range (Fig. 5). In the type area, on the west side of Ridge Hill Road in the Helena Valley, Prider (1948) described a series of ferruginous sandstone, ferruginous **conglomerate**, yellow sands, and **lateritic material**. These form a thin (probably less than 10 m) cover on the Ridge Hill Shelf and unconformably overlie the highly weathered **granite** and **dolerite** rocks of the Darling Scarp. Woolnough (1919) originally described the Ridge Hill Shelf as the top of a down-faulted portion of the lateritized Darling Plateau, and it was not until Prider (1948) carried out detailed mineralogical and textural studies that it was recognized as an erosional feature on which later marine and **fluvial** sediments had been deposited. Prider (1948) concluded that the Ridge Hill Shelf is a marine platform and that its associated deposits are beach and other **littoral** deposits that have been secondarily cemented by ferruginous cement.

Prider (1948) named the ferruginous sandstone and the basal ferruginous conglomerate the Ridge Hill Sandstone. Low (1971) later named the yellow sands the Yoganup Formation.

The Ridge Hill Sandstone is seen as a number of discrete outcrops along the Darling Scarp between Walyunga in the north and Forrestfield in the south. It is possible that other unmapped isolated outcrops may exist farther south. The outcrops range in elevation from 76 to 91 m AHD. Although the unit has no fossils, the geomorphological evidence favours an Early Pleistocene or Neogene age for the Ridge Hill Sandstone. Prider (1948) believed that the ferruginization of sandstone occurred in the Paleogene, and suggested a Lower Cretaceous age but, based on the known height range of the outcrops, Fairbridge (1953) correlated the level of the Ridge Hill Shelf with the Early Pleistocene Sicilian Terrace in Europe, which is a global (eustatic) feature dated about 170 000 years old. Playford et al. (1976) also favoured an Early Pleistocene age for the Ridge Hill Sandstone, and suggested a correlation with the Early Pleistocene heavy mineral strandline deposits at Eneabba, 250 km north of Perth.

The yellow sands of the Yoganup Formation (Low, 1971) outcrop discontinuously along the foot of the Darling Scarp from near Walyunga in the north to the Whicher Scarp near Busselton in the south. In the Perth Region the formation extends as much as 5 km westwards under younger deposits and has a maximum thickness of about 10 m. It was extensively eroded prior to deposition of the overlying Guildford Formation. The Yoganup Formation is a **prograding shoreline** deposit that includes a basal beach conglomerate, beach deposits, dunes, and occasional deltaic deposits. The base of the unit is at elevations of between 25 and 45 m AHD. Although it has not been dated paleontologically,

the Yoganup Formation is thought to be Middle Pleistocene in age based on stratigraphic and geomorphological evidence (Wilde and Low, 1978).

The best exposures of the deposits of the Ridge Hill Shelf in the Perth Region are found in the Walyunga area, in a similar geomorphic setting to that at Ridge Hill. The outcrops are well preserved within and immediately to the west of the Walyunga National Park and about 4 km north of Upper Swan (Figs 62 and 63). The Walyunga area is also notable for the presence of other deposits from which the early history of the Swan River can be deduced. Fletcher and Hobson (1932) and Seddon (1972) discussed the geology and geomorphology of the Walyunga area.

Ridge Hill Sandstone

The Ridge Hill Sandstone at Walyunga is found in two large deposits on private land either side of Walyunga Road (Fig. 63; see also Seddon, 1972), immediately to the west of the western boundary of Walyunga National Park. The sandstone is well-exposed in a large disused gravel pit south of Walyunga Road (Fig. 62) and in a number of breakaways both north and south of Walyunga Road. Both deposits slope gently to the west.

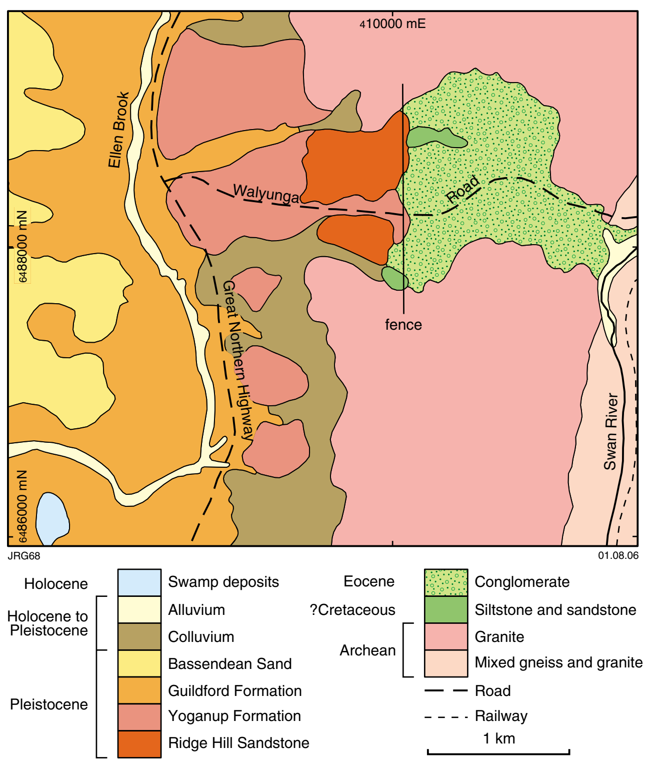

Figure 63. Geological sketch map of the Walyunga area

The Ridge Hill Sandstone forms a sequence of dark-red and purple, mottled yellowish brown, fine- to medium-grained, moderately sorted, quartzose sandstones (Fig. 64). These sandstones show no bedding and have no fossils. The sand grains within the rock mainly have smooth surfaces and are subrounded to well-rounded in shape. The sandstones contain fine- to medium-grained (and some coarse-grained) subrounded to rounded pebbles of vein quartz. These textures are typical of beach deposits, and the smoothed pebbles indicate marine abrasion of vein quartz derived from nearby Archean rocks. The colour of the sandstones is caused by ferruginization (impregnation with iron oxides).

Above the sandstone is a thin, discontinuous layer of lateritic material of yellowish brown to red, patchily purple, **nodular** ferruginous **duricrust**. The nodules are fine- to medium-grained gravel in size, and are identical in character to the underlying ferruginous sandstones, most consisting of subangular to subrounded, purple, fine- to medium-grained sandstone, and some of fine- to medium-grained, angular to subangular vein quartz. This indicates that the duricrust formed **in situ** over the Ridge Hill Sandstone during the process of lateritization, in which the upper parts of the sandstone became fragmented and further cemented with iron oxides. The matrix of the duricrust is a fine- to coarse-grained quartzose sand with some fine-grained, angular vein-quartz gravel.

Overlying the ferruginous duricrust is about 0.6 m of superficial, loose, medium- to coarse-grained, nodular and **pisolitic** lateritic gravel in a yellowish brown silty sand matrix.

Figure 64.
Detail of the Ridge Hill Sandstone at Walyunga, a moderately sorted quartz sandstone (MGA 409985E 6488270N)

If the Ridge Hill Sandstone is Early Pleistocene in age, the overlying ferruginous duricrust and associated gravels must have formed much later than the intensely weathered **lateritic profiles** typical of much of the Darling Plateau (see the Jarrahdale section of this guide), which developed during a Paleogene period of lateritization.

Yoganup Formation

Downslope from the outcrops of the Ridge Hill Sandstone, at about 30 m AHD, the ground forms an even, gentle slope before levelling out to the coastal plain. Deposits of the Yoganup Formation (Fig. 63) outcrop on this gently sloping surface, and there are excellent exposures in the sand pit on the eastern side of the Great Northern Highway, 600 m north of its junction with Walyunga Road (Fig. 62).

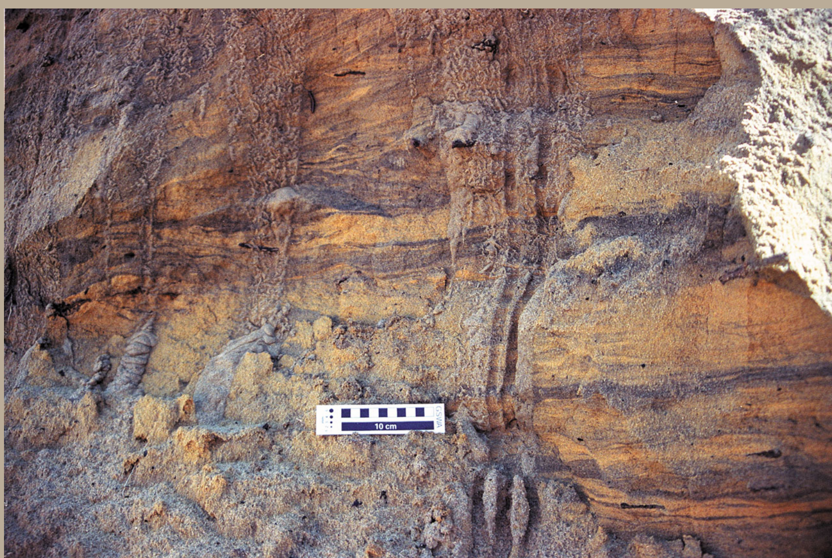

Figure 65.
Heavy mineral sand layers showing ripples and small-scale cross-bedding in the Yoganup Formation at Walyunga (MGA 408910E 6489135N)

About 8 m of sand is exposed in the working face of this pit. The sand is typically a yellowish brown, fine- to medium-grained, moderately to well-sorted, silty quartzose sand. The silt and clay content of the sand varies throughout the pit from about 15% in the east to as much as 35% in the west. The silt and clay content of the sand also varies on a much smaller scale. Some of these pockets with high clay content develop well-defined shrinkage cracks when dried out. This sand is of a uniform texture, with mostly little or no evidence of bedding, although some rare bedding structures are visible.

However, bedding structures are clearly visible in a 'vein' of darker sand in the north face of the pit. The sand here is the typical yellow sand, but is heavily stained by discrete layers of heavy minerals (Fig. 65). Within these layers it is possible to pick out ripples and small-scale cross-bedding. Layers of heavy mineral sands are also visible at the very top of the southeastern working face.

Figure 66.
Gravel layers in the Yoganup Formation at Walyunga (MGA 408910E 6489135N)

Throughout the quarry there are some thin layers of gravel (Fig. 66). These gravel layers are commonly associated with redder coloured sand containing more iron oxide. The gravel layers comprise fine- to medium-grained, subangular to rounded vein quartz, lateritic nodules, ferruginous sandstone, highly weathered **dolerite**, and nodules of weakly iron-cemented sand. These are materials that originated from the Ridge Hill Sandstone and Archean rocks upslope of the pit, and were probably deposited here by fluvial or colluvial activity.

The textural characteristics of the sand and presence of ripple marks and small-scale cross-bedding in the Yoganup Formation are consistent with its formation as a beach or nearshore deposit. However, the presence of the pit-wide layers of gravel indicates that there may have been a significant fluvial or colluvial input to the formation.

Eocene conglomerate

Extending over a large area within the Walyunga National Park is a thick deposit of unsorted conglomerate (Fig. 63). A road cutting on the south side of Walyunga Road (Fig. 62) shows the unit to consist of unfossiliferous, coarse gravel and cobbles, with some boulders of subangular to rounded quartz, granitic rocks, weathered dolerite, and banded chert set in a matrix of yellowish brown, mottled, angular to subangular, sandy silt and clay (Fig. 67).

Some of the clasts, particularly the quartz, show evidence of faceting to form **einkanter** and **dreikanter** pebbles, which are typically formed on open surfaces

Figure 67.
Detail of the Eocene conglomerate at Walyunga
(MGA $_{4}$10980E $_{64}$88635N)

such as stone pavements or rock plains in desert environments (both hot and cold) by sand blast and dust abrasion of the pavement stones. Some clasts, particularly those that are not highly weathered, also show evidence of possible **glacial striae**. These striae and the unsorted nature of the sediment led to the tentative suggestion that the conglomerate could be of glacial origin (Low et al., 1970), implying a Permian age, but there is no firm evidence for this.

Within the Perth Region there are similar small deposits of unsorted conglomerate on the flanks of incised valleys on the Darling Scarp along the eastern bank of the Canning River at Kelmscott; immediately north of Ye Olde Narrogin Inne at Armadale; along the Brookton Highway at Roleystone; and along Jarrahdale Road, west of Jarrahdale.

Outside the Perth Region, similar deposits are found at Kojonup, Muradup, and Calingiri (Wilde and Backhouse, 1977), Kirup (Taylor, 1971), and Harvey (Churchward and Bettenay, 1973). Churchward and Bettenay (1973) suggested a Mesozoic age for these deposits, and Playford et al. (1976), who named them the Harvey Beds, considered them to be Neogene or Early Pleistocene in age. However, Wilde and Backhouse (1977) were able to demonstrate an Eocene age for the fossiliferous deposits at Muradup and Calingiri, and suggested that, by comparison, deposits in similar geomorphological settings such as those at Walyunga may be of a similar age.

Along the valley of the Swan River at Walyunga Pool (labelled Boulder bed on Figure 62) there is a flat area covered with subrounded to well-rounded cobbles and boulders of granite, dolerite, and vein quartz, invariably unweathered or only slightly weathered. This deposit could be modern alluvium of the Swan River, associated with the river in full flood. However, its position here relative to the conglomerate described above (Fig. 63) may not be coincidental. Part of the boulder bed backs into the valley currently occupied by Spring Creek, west of Walyunga Pool, and may be the result of erosion of the conglomerate, and fluvial transportation of cobbles and boulders downhill to Walyunga Pool.

?Cretaceous siltstone

Outcrops of highly weathered siltstone containing some sandstone are located 500 m north of Walyunga Road along the fence line that marks the western boundary of the Walyunga National Park, and 400 m south of Walyunga Road along the same fence line (Fig. 63). There is no clear-cut evidence for the age of the outcrops — they were thought to be part of the Lower Cretaceous Leederville Formation, but Wilde and Low (1978) doubted this assumption and thought that they might be Neogene or Early Pleistocene in age. The northern outcrop forms an easterly trending low ridge with a steep north face and gentle south face; the southern outcrop is a large knoll.

The siltstones are purple and grey, mottled reddish and yellowish brown and, in places, contain pockets and lenses of fine- to medium-grained, poorly sorted, subangular to subrounded quartzose sandstone. Minor amounts of coarse-grained, subangular to subrounded vein-quartz gravel can be seen throughout the exposures. The deposits that form this sequence are all relatively immature, suggesting that they underwent minimal transport from their source, and the mixture of silt-, sand-, and gravel-sized materials indicates fluvial deposition.

Both outcrops have been intensely weathered and extensively lateritized. The siltstone and sandstone **saprolite** passes up into reddish brown and purple massive duricrust comprising fine- to medium-grained, subangular to subrounded quartz grains in a fine, sandy to silty matrix. **Core-stones** or remnants of the original siltstone, up to small cobble size, are evident throughout the saprolite. The lateritized surface comprises silty and variably sandy, medium- to coarse-grained, subangular to subrounded lateritic nodules.

The southern outcrop abuts and overlies Archean **granite**. Its morphology and position in the landscape suggests that it is a terrace remnant along the southern flank of a valley. The relationship between the northern outcrop and the surrounding geology is not clear, but it is at the same height as the southern outcrop, and close to the northern flanking Archean granite, so could also be a terrace remnant.

If the two outcrops are terrace remnants of a former, more extensive, fluvial deposit, they could only have been deposited by a Proto-Swan River flowing westwards across the Walyunga area, in which case these deposits are most likely late Mesozoic or early Cenozoic in age.

A wind gap

The morphology of the area between the Great Northern Highway and the Swan River at Walyunga is very distinctive. Walyunga Road follows an east–west valley, bound to the north and south by Archean granite that rises to more than 180 m AHD (Fig. 63). Along Walyunga Road, the ground rises up from about 30 m AHD at the Great Northern Highway to about 75 m AHD immediately east of the fence line that marks the western boundary of the Walyunga National Park. Here there is a flat area that can be traced continuously along the fence line, from the granites in the north to the granites in the south. To the east, the ground descends again to about 30 m AHD at the Swan River.

A valley of this size was obviously cut by a major river, but it is now abandoned and is preserved as a **wind gap** between the two present-day river systems (Fig. 63). The stream occupying this valley, Spring Creek, is clearly an **underfit stream**, far too small to have eroded such a large area — which was most likely cut by the Swan River at a time when it was significantly larger than today and westerly flowing. About 50 km west-southwest of Walyunga, in the Quinns Rock no. 1 offshore well, there is further evidence for a Swan River of significant size flowing west from Walyunga. Quilty (1974) described the presence of poorly sorted, silty, quartzose sandstones of the Early Eocene Mullaloo Sandstone Member of the Kings Park Formation. This instance is unusual in that it appears to be the only example of coarser material found offshore.

The Swan River would have migrated to its present course at a later date, possibly through **stream capture** by the **headward retreat** of a stream along the line of the present Swan River south of Walyunga. The flat area along the fence is a remnant of the original valley floor, and now forms an **interfluve** between the catchments of Ellen Brook and the Swan River.

Geological history of the Walyunga area

From the geology and landforms of the Walyunga area, the following geological history of the area can be inferred:

- Late Mesozoic or earlier (>135 Ma): a large, westerly trending valley was cut through the Darling Plateau and Darling Scarp by a Proto-Swan River.
- Cretaceous or Paleocene, or both (135–60 Ma): fluvial siltstones and sandstones were deposited.
- Paleocene or early Eocene (65–c. 45 Ma): the siltstones and sandstones were downcut and eroded, leaving terrace remnants.
- Eocene (53–34 Ma): conglomerate was deposited in a fluvial environment by a major Swan River flowing westwards towards what is now the offshore Perth Basin.
- Late Oligocene to early Miocene (34–20 Ma): a major period of intense weathering and lateritization affected the siltstone and sandstone deposits and the conglomerate deposit. During this period the major lateritic profiles of the Darling Range were also developed.
- The westward-flowing Swan River was captured and migrated to its present course.
- Early Pleistocene (1.65 – 0.75 Ma): sea level rose to about 75 m AHD and the Ridge Hill Sandstone was deposited in littoral nearshore and beach environments.
- The Ridge Hill Sandstone underwent lateritization.
- Middle Pleistocene (750–130 Ka): sea level fell to about 30 m AHD and the Yoganup Formation was deposited in littoral nearshore and beach environments, but with some fluvial or colluvial input from the east.
- The Swan River valley was downcut to modern-day levels in response to further drops in base level, and the former course of the Swan River developed as a wind gap.
- Boulder beds along the Swan River formed from the erosion of the Eocene conglomerate.

Getting there

Access to the Walyunga National Park is unrestricted, although an entrance fee is charged. However, outcrops and exposures of the Ridge Hill Sandstone, Yoganup Formation, and some outcrops of the ?Cretaceous siltstones and sandstones are on private land. Permission to enter private land must be obtained from the landowner.

To get to Walyunga National Park, travel along Great Northern Highway to the junction with Walyunga Road (MGA 408600E 6488575N), about 4 km north of the township of Upper Swan, and turn east onto Walyunga Road. Car parking is available in the Walyunga National Park. Roadside parking inside and outside the national park should be undertaken with caution.

GLOSSARY

Where possible, definitions are taken from Jackson (1997), Neuendorf et al. (2005), and Eggleton (2001), but some have been modified and simplified

Alluvial:	deposited by a stream or running water
Alluvial fan:	a low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan, deposited by a stream
Aminostratigraphy:	using amino-acid ratios to determine the stratigraphy of a geological rock sequence
Banded iron-formation (BIF):	a banded sedimentary rock with alternating iron-rich and chert-rich layers . Can be a good source of iron ore
Base level:	the theoretical limit or lowest level towards which erosion or wearing down of the Earth's surface constantly progresses
Beach ridge:	a low, essentially continuous, mound of beach or beach-and-dune material heaped up by the action of waves on the backshore of a beach; see also foredune
Beach rock:	a friable or crumbly to well-cemented sedimentary rock, formed in the intertidal zone
Blowout:	a saucer- or trough-shaped hollow or depression formed by wind erosion of a dune, especially in an area of shifting sand
Brecciated:	a rock structure marked by an accumulation of angular fragments; rock type is called breccia
Calcarenite:	a limestone consisting predominantly of sand-sized carbonate grains
Calcrete:	a calcareous duricrust
Carbonate:	a) a sediment formed by the organic or inorganic precipitation of carbonates of calcium, magnesium, and iron; for example, limestone and dolomite b) a mineral compound of calcium (or magnesium or iron), with carbonate ($CaCO_3$)
Chronostratigraphy:	the organization of rock strata into units on the basis of their age or time of origin
Clastic sedimentation:	a new sedimentary rock formed by the accumulation of fragments derived from the weathering of pre-existing rocks or minerals
Cleavage:	the tendency of a rock to split in a particular direction, or along a surface
Colluvial, colluvium:	any loose soil or rock material deposited by mass wasting
Conformity:	deposition of sedimentary layers in an orderly fashion without time lapses or tilting or folding; such rocks are said to be conformable
Conglomerate:	a coarse-grained sedimentary rock composed of rounded to subangular fragments larger than 2 mm in diameter, set in a matrix of fine-grained particles
Core-stone:	a block of rock formed by subsurface weathering but entirely separated from its bedrock
Craton:	a large, ancient region of the Earth's continental crust that has been stable and little deformed for 2.5 billion (2500 million) years. In Western Australia, the Yilgarn Craton and Pilbara Craton are examples

Cross-bedding:	a term for criss-cross bedding layers in sedimentary deposits, produced by the migration of ripples or dunes on bedding surfaces
Crystalline rock:	an igneous or metamorphic rock, not a sedimentary rock
Cuspate beach-ridge plain:	the largest cusp, occurring as a cape or as a broadly triangular point of sand or shingle, with the apex pointing seaward, along an open coast
Dolerite:	a fine-grained, dark-coloured, intrusive igneous rock with an ophitic texture, composed of labradorite (a feldspar) and pyroxene
Doline:	a basin or funnel-shaped hollow in limestone
Dreikanter:	a double-pointed wind-worn stone with three curved faces intersecting in three sharp edges and resembling a Brazil nut (from German: drei = three)
Duricrust:	a hard crust on the surface of a soil in a semi-arid climate. May also be a hard layer just below the surface
Einkanter:	a wind-worn stone with only one face or a single, sharp edge (from German: ein = one)
Eolian:	formed by the wind, especially said of deposits such as dune sand
Erosion terrace:	a terrace produced by erosion
Estuarine:	formed or living in an estuary
Fissile:	said of a rock capable of being easily split along closely spaced planes
Flow stone:	a general term for any deposit of calcium carbonate or other mineral formed by water flowing on the walls or floor of a cave
Fluvial/fluviatile:	of or formed by a river
Foraminifera:	minute organisms with a test or shell composed of secreted calcite
Foredune:	a coastal dune oriented parallel to the shoreline, lying on the landward margin of a beach
Gastropod:	a mollusc shell belonging to the class *Gastropoda*, e.g. snail, abalone, limpet
Glacial striae:	a series of delicate, finely cut, commonly straight and parallel furrows or lines inscribed on a bedrock surface by the rubbing of rock fragments embedded a1.7d of a rock or soil hardened or consolidated by pressure, cementation, or heat
In situ:	in its original position
ka:	thousand years
Karstic:	describes the type of topography that is formed on limestone, and other rocks, primarily by dissolution, and that is characterized by sinkholes, caves, and underground drainage
Large igneous province:	A region characterized by emplacement of massive volumes of predominantly mafic extrusive and intrusive rocks
Lateritic materials:	a collective term for the ferruginous (or iron-rich) and aluminium-rich part of a lateritic profile
Lateritic profile:	a vertical sequence of regolith showing some or all of the following, from the base upward: bedrock, leached white zone, mottled red and white zone, porous crust often with gravel or pisolites
Lateritic weathering:	the process, which, through the influence of gravity, the atmosphere, hydrosphere and/or biosphere at ambient temperature and atmospheric pressure, modifies rocks, either physically or chemically, to produce a lateritic profile
Lateritization	process of transforming a (near)-surface layer (rock or soil) into lateritic material
Leaching:	the separation, selective removal, or dissolving-out of soluble materials from a rock or orebody by the natural action of percolating water

Lithified:	consolidated from a loose sediment to a solid rock
Littoral:	refers to the zone between high water and low water in the ocean environment
Longshore current:	an ocean current caused by the approach of waves at an angle to the coast
Ma:	million years
Macrofossil:	a fossil large enough to be studied without the aid of a microscope
Magma:	naturally occurring molten or partially molten rock material
Magmatism:	the development and movement of magma, and its solidification into igneous rock
Marine transgression:	the spread or extension of the sea over land areas
Metagranite:	A granite that has undergone metamorphism
Metamorphic rock:	a rock derived from another pre-existing rock by changes in temperature, pressure, and stress, generally at depth in the crust; the process is called metamorphism
Microporphyritic:	said of a texture of a porphyritic igneous rock in which the phenocrysts are of microscopic size
Mollusc/molluscan fauna:	a solitary invertebrate creature with a hard external shell that is bilaterally symmetrical; includes many familiar shells such as limpet, mussel, snail, oyster
Monadnock:	an upstanding rock or hill conspicuously above the general level of a peneplain
Monzogranite:	a variety of granite
Neptunian dyke:	a sedimentary dyke formed by infilling of sediment (often sand) in an undersea fissure or hollow
Nodular:	composed of generally pebble-sized lumps of regolith, distinguished by their commonly smooth surface, sometimes with a contrasting cortex. Also: nodule
Notch:	a deep, narrow cut or hollow along the base of a sea cliff near the high-water mark, formed by undercutting due to wave erosion and/or chemical solution, and above which the cliff overhangs
Ophitic texture:	an igneous rock texture where the pyroxene grains enclose numerous thin feldspar laths (common in dolerite)
Oxygen Isotope Stage:	Oxygen isotope stages are based on mid-points of temperature curves derived from data from deep-sea cores. Change in the oxygen isotope ratio is a function of temperature as well as a reflection of global-scale ocean chemistry, which changes with ice build-up on the continents during glaciations. Measurement of the oxygen isotope ratios in benthic foraminifera give a measure of how much ice accumulated on land, from which oxygen isotope stages are calculated
Paleosol:	a soil with distinctive morphology that has formed on a landscape in the past resulting from a soil-forming environment that no longer exists at the site
Parabolic dune:	a sand dune with a long, scoop-shaped form, convex in the downward wind direction so that its horns (or arms) point upwind, whose ground plan approximates the form of a parabola
Pedogenic calcrete:	calcrete formed within the soil by soil-forming processes
Pedologic horizon:	soil horizon
Pegmatite:	a very coarse grained igneous rock with large interlocking crystals, usually found as irregular dykes, lenses, or veins

Peneplain:	a low, nearly featureless, gently undulating land surface of considerable area formed by prolonged subaerial erosion
Phenocryst:	relatively large conspicuous crystals in a porphyritic rock
Piedmont zone:	a zone formed or lying at the base of a mountain range
Pisolith:	pea gravel from the lateritic profile. In the Perth Region found east of the Darling Scarp over Archean rocks
Pisolitic:	refers to the texture of a rock made up of pisoliths
Porphyritic:	the texture of an igneous rock in which large crystals are set in a finer grained groundmass
Prograding shoreline:	a shoreline that is being built forward or outward into a sea or lake by deposition and accumulation of sand or sediment
Quartzite:	a) a very hard sandstone where the quartz grains have been solidly cemented by silica b) a metamorphosed recrystallized sandstone
Raised beach:	an ancient beach occurring above the present shoreline and separated from the present beach
Regression:	the retreat of the sea from land areas and the evidence for it (opposite: transgression)
Rhizolith:	a hollow concretion-like mass, usually cylindrical, that formed around the root of a living plant
Ria:	a long, narrow inlet or arm of the sea that has been produced by drowning of the lower part of a river valley or of an estuary
Rift valley:	a long narrow continental trough that is bounded by normal faults
Saprolite:	weathered rock in which the fabric of the parent rock is still visible
Scarp:	a line of cliffs produced by faulting or erosion
Sea-floor spreading:	a geological theory that the ocean crust is increasing in area by upwelling of magma along the mid-ocean ridges
Sea stack:	a pillar of rock rising on all sides above the wave-cut platform on which it formed
Sedimentary rock:	a rock formed by the compaction of loose sand and sediment
Sinkhole:	a depression in a karst area, commonly circular
SRTM:	Shuttle Radar Topography Mission. SRTM has obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. See the website. SRTM is an international project of the National Aeronautics and Space Administration (NASA)
Stalactite:	a conical or cylindrical cave formation that hangs from the ceiling of a cave
Stalagmite:	a conical or cylindrical cave formation that grows upward from the floor of a cave by the action of dripping water
Stratigraphy:	the science of rock strata. It is concerned not only with the original succession and age relations of the layers of rock, but also with their form, distribution composition, fossil content, geophysical, and geochemical properties
Stream capture:	the natural diversion of the headwaters on one stream into the channel of another stream with greater erosional power
Stromatolite:	a laminated structure, produced by sediment trapping or binding, built mainly by cyanobacteria (sometimes known as blue-green bacteria)
Subaerial:	conditions or processes (especially erosion) that operate in the open air
Swale:	a long, narrow, generally shallow, trough-like depression between two beach ridges, aligned roughly parallel to the coastline

Swallet:	the opening through which a sinking stream loses its water to the subsurface
Swash zone:	the sloping part of the beach that is alternately covered and uncovered by the uprush of waves
Tethys:	an ocean that once occupied the general position of the Alpine Himalayan area
Thalweg:	the longitudinal profile of a stream or valley
Tombolo:	a sand or gravel bar or barrier that connects an island with the mainland or with another island
Transgressive/transgression:	relating to the spread or extension of the sea over land areas and the consequent evidence of such advance. Opposite: regression
Type section:	the originally described sequence of rocks that make up a named rock unit or stratigraphic unit (as type area)
Unconformity:	a substantial break or gap in the geological rock record where a rock unit is overlain by another that is not next in the stratigraphic succession
Unconsolidated material:	a sediment whose particles are not consolidated; can be crumbled or deformed with the fingers
Underfit stream:	a stream that appears to be too small to have eroded the valley in which it flows
Vermiform:	Having the form of a worm. A fabric consisting of tubes, pipes or worm-shaped voids that may be filled or partly filled
Wave-cut platform:	a gently sloping surface produced by wave erosion, extending into the sea or lake from the base of the wave-cut cliff
Weathering	the physical and chemical disintegration of a rock, usually in situ, by water, wind, and ice
Wind gap:	a former water gap, now abandoned by the stream that formed it
Xenolith:	a fragment of country rock within a plutonic or volcanic rock. A rock fragment foreign to the igneous rock in which it is embedded

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INDEX

Period	Epoch	Stage	Sub-stage	Glacial and Interglacial	Oxygen Isotope Stage	Lower boundary age (ka)
Quaternary	Holocene			Postglacial	1	10
	Pleistocene	Late Pleistocene		Last glacial	2	25
					3	60
					4	75
				Last interglacial	5	130
		Middle Pleistocene	Late	2nd last glacial	6	190
				2nd last interglacial	7	240
				3rd last glacial	8	300
			Middle	3rd last interglacial	9	340
				4th last glacial	10	
				4th last interglacial	11	420
				Pre-4th last integlacial	12	480
			Early		13	
					14	
					15	
					16	
					17	
					18	
					19	750
		Early Pleistocene			20	
					. . . .	
					36	1810

Expanded geological time scale covering the Quaternary period (see also complete time scale inside the front cover)

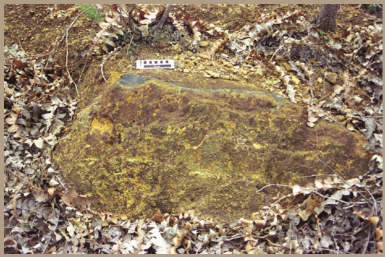
About this guide

Stretching from the ocean to the eastern hills, the Perth Region has coastal landscapes, river-valley landscapes, and forested hilly landscapes that reflect the diverse geology beneath.

This field guide covers some of the classic geological localities near Perth — for instance Cape Peron has preserved evidence for sea-level changes that have featured in scientific discussions for over 50 years. The guide describes the landscape and rocks and gives explanations on how they formed. Close-up photos and diagrams help the reader recognize and interpret the localities.

'This is a handy little guide for anybody with an interest in understanding their local landscape and local geology.'

Dr Tim Griffin, *Director, Geological Survey of WA*



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